JACKSON, GROVE & GRAY

Transformer Connections

Electrical Engineering

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TRANSFORMER CONNECTIONS

BY

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THESIS

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Ralph Nathaniel Jackson, Chester Hayward Grove

and Fred Jay Gray

ENTITLED Transformer Connections

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Bachelor of Science in Electrical Engineering

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INTRODUCTION.

It is proposed in this paper to state the effect produced by numerous methods of connecting transformers. In practice it is an easy matter for a station engineer to determine whether a combination of transformers is correct or not by simply applying the voltage; but in case the test should prove wrong it is not always an easy matter to determine where the error exists. In the treatment of this subject stress was laid more upon the relative magnitude and direction of the currents and voltages, than upon their accuracy.

Such, then, is the purpose of this paper. It is only an elementary discussion of the subject, but yet, since it treats of a branch of alternating current phenomena of which very little has been published, and which is of interest to the engineer, the writers feel justified in offering it to such as may chance to read it, with their apologies.

We wish to express our warm appreciation and thanks to Mr. H. M. Turner whose advice and cooperation in bringing out the work have materially assisted the authors.

TRANSFORMER CONNECTIONS

SINGLE PHASE.

The transformer consists primarily of three parts: two separate electrical circuits interlinking with a common magnetic circuit.

The theory of the constant-potential transformer is easily explained if we neglect the small effect of resistance drop in the windings, leakage of magnetic flux and iron losses. The primary of the transformer is connected to a source of power in a manner that would be practically a short circuit, if it were not for the fact that the periodic variation of the current causes the flux produced by the current to generate a counter e.m.f. This counter e.m.f. will hold the current down to a value on no load just sufficient to produce that value of flux necessary to generate an e.m.f. in the primary equal and opposite to the impressed e.m.f.

This flux is also interlinked with the secondary winding and hence the same e.m.f. is induced in each turn of wire on the secondary. If E_p is the impressed e.m.f., then,

$$\frac{E_p}{N_p} = e = \text{primary e.m.f. per turn,}$$

where N_p is the number of primary turns. Then if N_s is the number of secondary turns,

$$E_s = N_s e = \text{secondary e.m.f.}$$

and

$$\frac{E_p}{E_s} = \frac{N_p}{N_s} = \text{ratio of transformation.}$$

If N_p is greater than N_s the transformer is called a "step-down" transformer, while if N_p is less than N_s it is called a "step-up" transformer.

[illegible]

In the design of transformers the following equation is found reliable:

Let N = Total number of turns in series,

ϕ = Instantaneous and Φ the maximum value of magnetic flux,

A = Cross section of magnetic circuit in square inches,

f = Frequency in cycles per second,

B = Lines of force, or flux density per square inch,

E = Effective e.m.f.,

Considering a sine wave of flux as flowing in the magnetic circuit then,

$$\phi = \Phi \sin \omega t, \quad \text{differentiating,} \quad \frac{d\phi}{dt} = \omega \Phi \cos \omega t.$$

The instantaneous value of the counter e.m.f. $= -N\omega\Phi \cos \omega t$, and the maximum value of the counter e. m. f. $= N\omega\Phi$, and the effective value of the counter e. m. f. $= .707\ N\omega\Phi$.

But since $\omega = 2\pi f$,

then

$$E = .707\ N\ \Phi\ 2\pi f = 4.44\ f\ N\ \Phi \text{ abvolts, or}$$

$$= 4.44\ f\ N\ \Phi\ 10^{-8} \quad \text{volts.} \qquad (1)$$

If the volts, frequency, cross section of core, and the flux density are known, we have,

$$N = \frac{E\ 10^8}{4.44\ f\ B\ A} \text{ total turns.} \qquad (2)$$

If the volts, frequency, and number of turns are known, then we have,

$$\Phi = \frac{E\ 10^8}{4.44\ f\ N} \text{ maximum value of flux.} \qquad (3)$$

Magnetic densities of transformers vary considerably with the different frequencies, designs, and also among different parts and types of the same transformer. With higher densities, of large

units, trouble is experienced upon closing the switch because of an instantaneous current. This is due to the fact that if the transformer is being worked near its saturation point the switch may have been last opened at a rather high point on the curve and the cycle may be just opposite when the circuit is again closed, thus consuming energy to not only demagnetize the core but also to magnetize the iron in the opposite direction.

The current densities employed in transformers vary from one thousand to two thousand circular mills per ampere.

The efficiency of a transformer is shown by,

$$\text{Efficiency} = \frac{\text{out-put}}{\text{output} + \text{core loss} + \text{copper loss}}$$

The two principle precautions which must be observed in connecting two transformers are, that the terminals must have the same polarity at a given instant, and the transformers should have practically identical characteristics. As regards the later condition, suppose a transformer with a two percent regulation is connected in parallel with one of three percent regulation; at no load the transformers will give the same e.m.f. at the terminals of the secondary but at full load one will have a secondary e.m.f of, say, ninety eight volts, while the other has an e. m. f. of ninety seven volts. The result is that this one volt difference will disturb the power factor, efficiency, and combined capacity; in which case it is much better to operate the secondaries of the two transformers separately. In this case the load will be unevenly distributed, the transformer with the highest secondary voltage taking the largest load. In order to determine the polarity of two transformers proceed with the parallel connection as if everything were all right, but connect the ter-

minals together with fuse wire, then close the primary switch. If the fuse blows, the connections must be reversed; if it does not blow, then the connections may be made permanent. The same result may be obtained by closing one side of the secondary and measuring the voltage across the opening on the other side. If it is zero, the connection may be made, if it is twice the voltage across one coil, the connections must be reversed.

FIGURE 1.

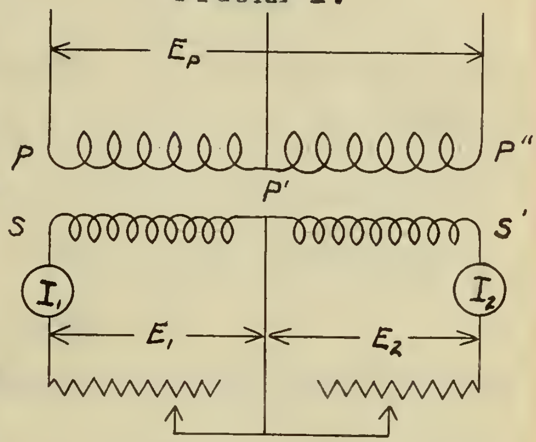


Figure 1 shows one transformer which has two secondary coils connected in series. If this transformer be of the core type and the two coils arranged on different limbs of the core, it will be advisable to have the fuses in the middle wire considerably smaller than those on the outside circuits. The reason for this is, that should one of the fuses on the outside circuits blow, say, for instance the fuse at S, the secondary circuit through this half-section will be open circuited, and the primary coil corresponding to this section will have a greater impedance than the other half of the coil, the inductance of which will be neutralized by the load on the other half of the secondary coil. The result will be that the counter e.m.f. of the primary section, P, will be greater than that of section, P", because the two sections are in series with each other, and the current must be the same in both coils, therefore, the difference of potential between the primary terminals, PP', will be greater than that between P'P", consequently the secondary voltage S' will be greatly lowered. The following data shows this unbalanced condition of voltage for an unbalanced load:

PRIMARY		SECONDARY			
	E_p	E_1	E_2	I_1	I_2
No Load	454	45.6	45.6	0.0	0.0
Load Balanced	454	45.	45.2	4.30	4.28
Load Unbalanced	454	42.7	48.2	10.33	2.20

From this we see that the voltage on coil number one decreased as its load increased and likewise the voltage on coil number two increased as its load became the smaller of the two. To overcome this undesireable condition each coil is divided into two sections; then these sections are placed on opposite legs of the transformer, making each leg have one half the load of each coil.

By the use of two single phase transformers a large number of voltages may be obtained. Assume a ratio of ten to one for this discussion and take the voltage rating of the primaries as 1000 volts, giving 100 volts on the secondaries. The following connections may be used providing the transformers have the same charteristics:

1. Primaries in series - secondaries in series, giving a transformation of 2000 to 200, or to 100 if the middle wire is brought out.

2. Primaries in series - secondaries in parallel, giving a ratio of transformation of 2000 to 100 volts.

3. Primaries in parallel - secondaries in parallel, giving a ratio of transformation of 1000 to 100 volts.

4. Primaries in parallel - secondaries in series, giving a ratio of 1000 to 200 or to 100 if the middle wire is brought out.

The three wire system is a very good one wherever it is possible to divide the load into two equal, or nearly equal, parts,

because it allows current to be delivered at one voltage, say 100 volts, with the same percent drop as though double the voltage were used with the load balanced. Figure 2 shows the balanced three-wire

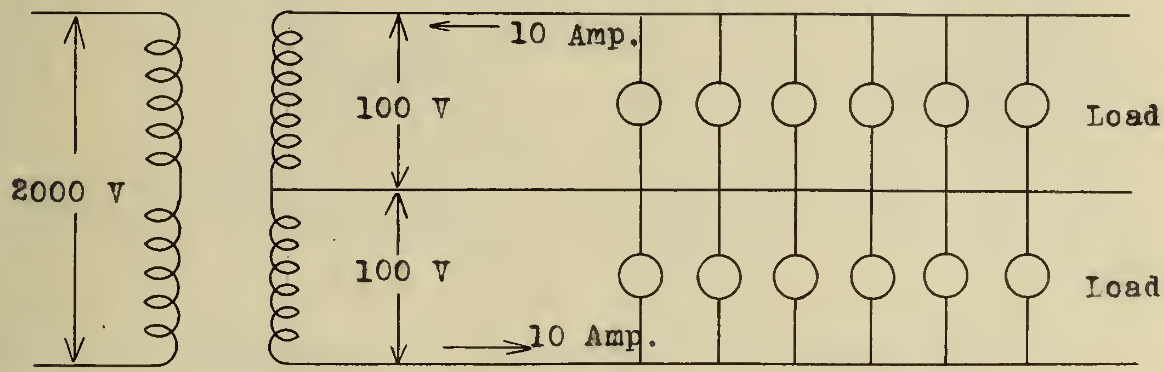


FIGURE 2

system of distribution. In practice the middle main is usually made of the same size wire as each outside main, and each out-side main need be only one quarter as heavy as would be required to supply the same number of lamps in simple parallel system using the 100 volts; therefore to supply a given number of lamps in the three-wire system, as shown in figure 2, requires only three-eights as much copper as would be required in the simple parallel system with same percent drop in voltage.

It is not advisable to use two transformers as shown in figure 2, that is with their primaries in series, because they would not be used this way unless they were rated for 1000 volts each and if so, it involves a high voltage strain inside the transformers, between the high and low tension windings for which the coils were not designed. It should be used in case of necessity only.

It sometimes is desirable to increase or decrease the voltage by a small amount at some point on a line. To properly accomplish this a "boosting " or "lowering" transformer, as the case may be, should be used. In the case of a "boosting" transformer, as

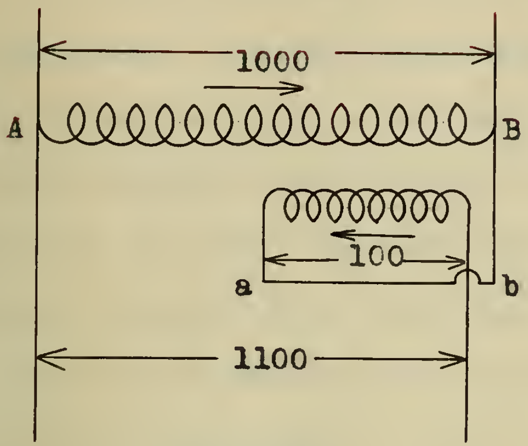


FIGURE 3.

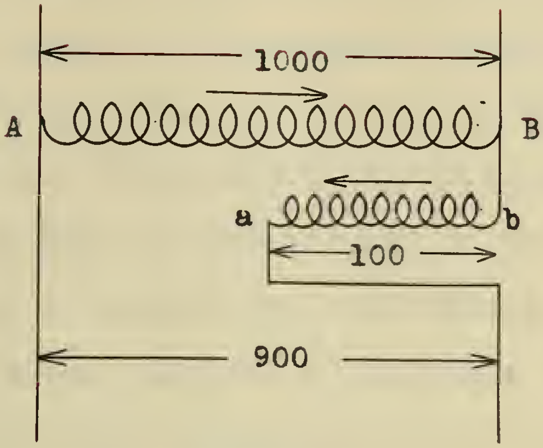


FIGURE 4.

shown in figure 3, one side of the secondary (a), is connected to the opposite side of the primary (B), and the other side of the secondary (b), forms one side of a new line of which the other side is (A), and which has a voltage equal to the primary voltage plus that of the secondary. If a "lowering" effect is desired the corresponding sides of a secondary and primary, (B) and (b) of figure 4, should be connected together and the other two terminals, (A) and (a), will then be the main line having a voltage of the secondary and primary difference. The following data was taken for the two conditions, the subscripts on the voltages refering to the above figures 3 and 4.

Boosting voltage	E_{Ab}	E_{ab}	E_{AB}
Using one secondary	506	102	412
Using two secondaries	600	182	420
Lowering Voltage			
Using one secondary	320	102	420
Using two secondaries	218	170	408

In transforming over small range of voltage, or for starting purposes, an auto-transformer is found to be decidely cheaper than a transformer, the reason being, that the same winding is used for both primary and secondary current. For a given transformation of energy, of small voltage range, an auto-transformer may be considerably smaller than any other type of transformer, and consequently its losses will be less and the efficiency higher. The rating of an auto-transformer depends upon its full-load current and its voltage. At full load the primary and secondary currents are so nearly in opposition that in this discussion they can be considered so. Let us consider how the rating varies with the voltage transformation:

Let e = primary e.m.f.,

i = primary current,

e' = secondary e.m.f.,

i' = secondary current.

Neglecting the core loss which is a small percent at full load then,

$$ei = e'i', \qquad \text{or } i' = \frac{e}{e'}\, i.$$

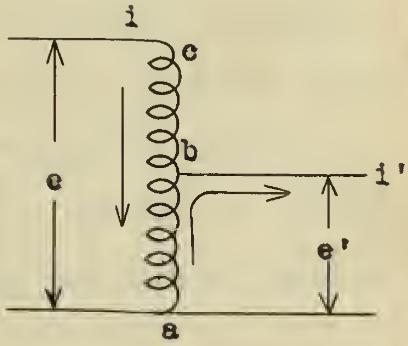


FIGURE 5.

Referring to figure 5 it is seen, that in winding bc we have the primary current i. In the winding ab we have the difference between the primary and secondary current. Thus we can write,

$$i - i' = i\left(1 - \frac{e}{e'}\right)$$
$$= \frac{e' - e}{e'}\, i$$

We have therefore that the winding bc should have sufficient number of turns for ($e - e'$) volts, and sufficient current carrying

capacity for i amperes. Thus the rating of section bc is given by the expression,

$$(e - e') i.$$

Similarly the rating of section ab is found,

$$e' \frac{e' - e}{e'} i = (e' - e) i$$

$$= - (e - e') i.$$

Thus the rating of the transformer is,

$$i (e - e')$$

and the percentage cost rating of an auto-transformer and a transformer is given by,

$$\frac{i (e - e')}{ie} = \frac{(e - e') 100}{e}$$

For $e' = 10$ percent, the rating is $= 90$ percent.

$e' = 25$ percent, the rating is $= 75$ percent.

$e' = 50$ percent, the rating is $= 50$ percent.

$e' = 75$ percent, the rating is $= 25$ percent.

$e' = 90$ percent, the rating is $= 10$ percent.

$e' = 100$ percent, the rating is $= 0$ percent.

The above figures show that if there is a slight change in voltage there is a very great advantage in the use of an auto- transformer over the transformer. However if the secondary voltage is much smaller there is very little to be gained as the entire winding has to be designed for heavier carrying capacity and higher insulation.

The series transformer is used mostly in connection with alternating-current ammeters and wattmeters where the voltage of the circuit is so high as to render it unsafe to connect the instrument directly into the circuit and also when the current to be measured is

greater than the capacity of the instrument. The density in the series transformer changes with varying conditions of loading hence for accurate readings it is necessary to work the iron in the series transformer below the saturation point. In some of the well designed series transformers the ratio is practically correct for loads within the rated limits of the transformer. Data was taken on a 40 to 5 ratio series transformer and the results show that this ratio was nearly constant for all loads, as shown by the following;

PRIMARY	SECONDARY	CHECK
I_p	I_s	$40/5 \times I_s = I_p$
39.5	5	40.0
37.5	4.55	36.4
33.4	4.22	33.7
30.9	3.90	31.2
26.1	3.3	26.4
23.2	2.85	22.8
17.8	2.2	17.6
15.0	1.83	14.6
11.5	1.44	11.5
6.4	.80	6.4

Series transformers might be used in parallel to step the current down farther than one alone will do, but great care should be taken in this case to see that the readings obtained are correct as any error in the first transformer will also be present in the second together with the error of the latter. These errors would add on to each other if the transformers are similar. Because of these difficulties, series transformers should never be used in parallel when any other method could be used.

TRANSFORMER CONNECTIONS

TWO PHASE.

So far as transformers are concerned in two phase distribution, each circuit may be considered independently of the other, that is as though each primary and secondary were only a straight single-phase system. One transformer is connected to one primary phase, and supplies one secondary phase, independent of the other phase, and the other transformer is connected to the other primary phase, supplying the other secondary phase.

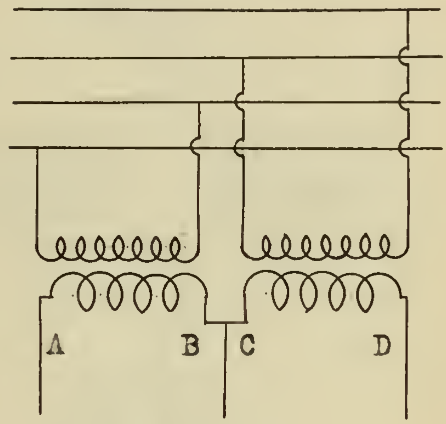


FIGURE 6.

In connecting transformers to a two phase system, the object is to get the two phases as nearly balanced as is possible. A method of connection used in two phase work is shown in figure 6. This method is called the four-wire primary and three wire secondary connection. The middle wire in this case is about one half larger than either out side wires. So long as the two transformers are not connected in parallel it makes no difference which secondary wire of either transformer is connected to a given secondary wire of the other transformer. That is terminals A and D could have been connected together instead of terminals B and C.

The two circuits being 90 degrees apart, the voltage between terminals A and D is the square root of two or 1.41 times that between any out side wire and neutral. This is seen from the vector diagram shown in figure 7. The current in the middle wire, since the currents have the same

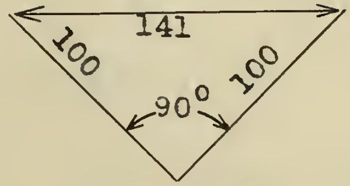
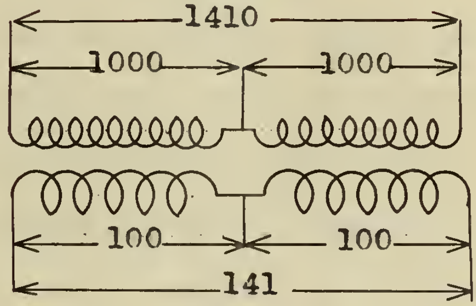


FIGURE 7

phase relation to each other as the voltages, is 1.41 times that in either out side wire.

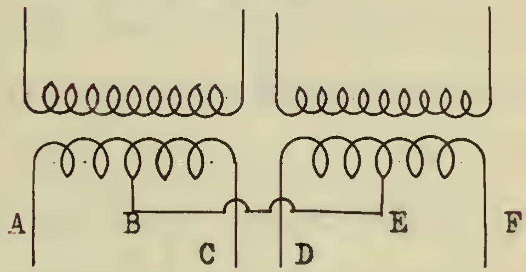
Another method of connecting transformers in two phase is to have both primary and the secondary connected in three wire method as shown in figure 8.

FIGURE 8.



Still another method of connection is shown in figure 9. This combination gives two main circuits and if other voltages are desired it is evident from the vector diagram 9a that there are various voltages to be readily obtained.

FIGURE 9.



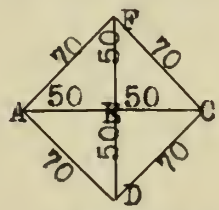


FIGURE 9a

It often becomes necessary to transform from two phase to three phase. One of the most common ways of doing this, is by a

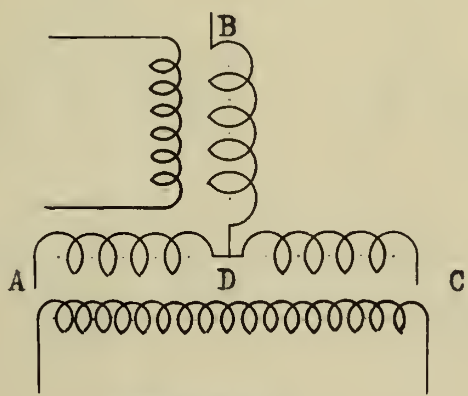


FIGURE 10.

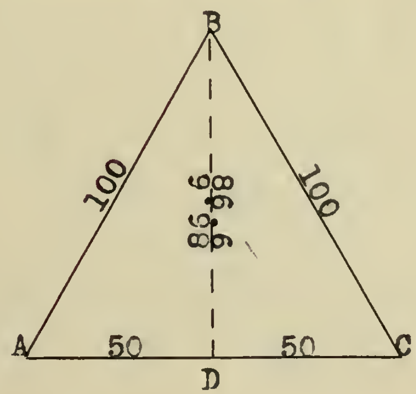
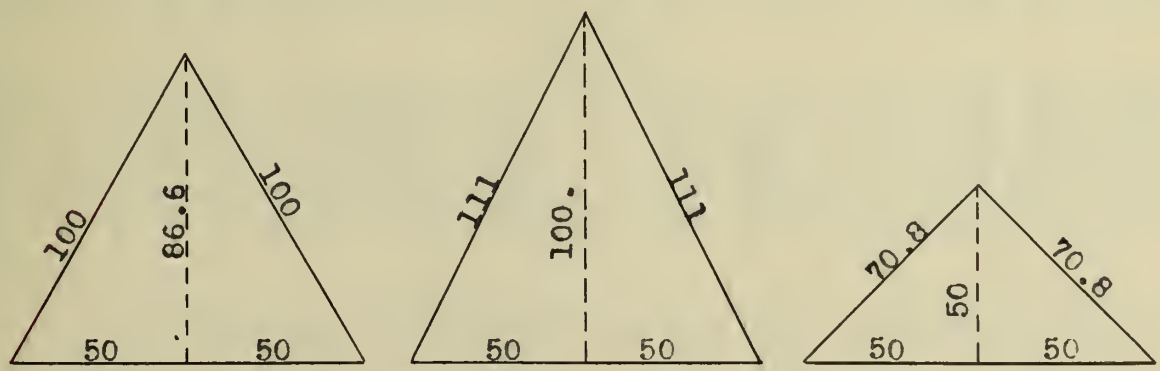


FIGURE 11.

"Scott" transformer, as shown in figure 10. This system requires

two transformers one with 100 turns on its secondary and the other with 86.6 turns on its secondary, or the number of turns on the secondaries must be in the proportion of 100 to 86.6.

In case, however, there are only two similar single phase transformers at hand and a three phase induction motor is to be run, then the two transformers may be connected as in the case of the "Scott" transformation. This will not, however, give the correct ratio of voltages across each phase because the 86.6 portion of the winding is not available in the ordinary single phase transformer. Instead of using the 86.6 portion there is only available the whole secondary or one half of it. Figure 11 shows the existing conditions when the vector diagrams are drawn out with these ratios of windings. The relative effect on the operation of a three phase induction motor using the above ratios is shown by the following diagrams and data;



CASE 1. CASE 2. CASE 3.

The following data shows the relative effect upon the operating characteristic of a three phase Induction motor when by a "Scott" method of transformation with the following ratios of secondary coils:

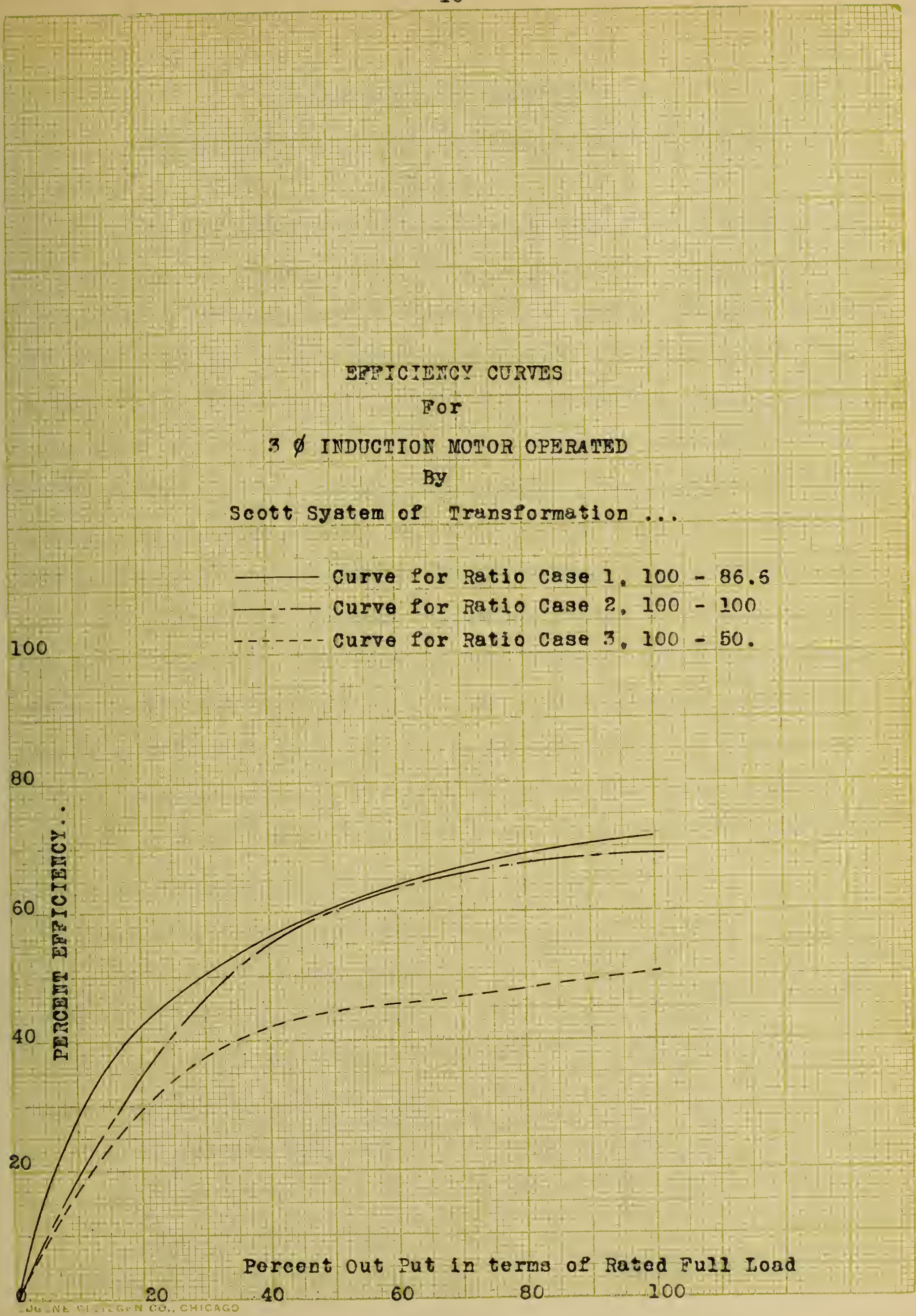
Case 1 Ratio of Secondary coils = 86.6 to 100

Case 2 Ratio of Secondary coils = 100 to 100

Case 3 Ratio of Secondary coils = 50 to 100.

Input to Transformer and Motor K.W.			Motor Current Ampere.			Motor E.M.F. Volts.						Percent Load		
W_A	W_B	W_{AB}	I_A	I_B	I_C	E_a	E_b	E_c	RPM.	Wt.	KW.	In-put.	Out put	Eff. %
						CASE 1.								
0.8	0.48	1.28	13.6	15.5	13.8	114	116	114	1164	34.5	0.45	34.3	12.1	35.1
1.0	0.60	1.60	13.8	16.4	14.8	112	116	117	1170	40.0	0.67	43.0	18.0	42.0
1.24	0.80	2.04	15.0	17.6	16.0	113	116	116	1180	46.0	1.05	54.6	28.2	51.4
1.74	1.20	3.02	18.0	19.8	19.0	114	116	115	1160	58.0	1.75	81.0	47.0	58.0
2.20	1.60	3.80	20.0	24.0	22.5	113	116	118	1150	70.0	2.50	102.	67.0	65.6
2.60	1.71	4.51	22.7	27.0	26.0	113	116	117	1174	80.0	3.18	121.	85.3	70.2
						CASE 2.								
0.40	0.88	1.28	23.2	11.0	14.8	114	116	118	1140	30.0	0.04	34.3	11.5	3.4
0.48	1.56	2.04	24.0	13.6	14.6	117	120	121	1170	40.0	0.67	54.6	18.0	32.8
0.80	1.62	2.42	25.4	17.0	14.0	116	113	117	1150	50.0	1.27	65.0	34.0	52.4
1.20	1.80	3.00	28.0	20.0	14.8	115	116	117	1160	60.0	1.90	80.5	51.0	63.3
1.52	2.40	3.92	30.0	23.2	16.5	112	116	118	1150	70.0	2.56	105.	68.6	65.3
1.92	2.52	4.44	32.0	26.0	18.5	116	116	120	1130	80.0	3.06	119.	82.0	69.1
2.32	3.12	5.47	35.0	28.0	19.5	114	117	120	1160	90.0	3076	146.	101.	69.2
						CASE 3.								
2.08	-.80	1.28	18.0	34.0	37.0	77.	80.	115	1200	30.0	0.05	34.3	12.1	2.2
2.64	-.04	2.60	16.0	35.5	38.0	76.	80.	115	1224	40.0	0.70	69.6	18.8	27.0
3.20	.04	3.34	14.0	36.0	41.5	75.	77.	114	1230	50.0	1.35	89.5	36.2	41.6
3.92	.40	4.32	14.0	37.0	47.0	75.	77.	111	1190	60.0	1.95	116.	52.3	45.5
4.00	.88	4.88	16.0	41.0	48.0	70.	78.	111	1182	65.0	2.24	131.	60.0	46.0

In order to run this test an O D type of transformer was used which made a good basis to show the relative effect for the same conditions were available in the same two O D transformers. From the efficiency curve it is seen that the above second case comes very near to the Scott method which requires specially designed transformers, hence in some instances this second case is used.


EFFICIENCY CURVES
For
3 Ø INDUCTION MOTOR OPERATED
By
Scott System of Transformation ...
Curve for Ratio Case 1, 100 - 86.6
Curve for Ratio Case 2, 100 - 100
Curve for Ratio Case 3, 100 - 50.
PERCENT EFFICIENCY..
100
80
60
40
20
0
20
40
60
80
100
Percent Out Put in terms of Rated Full Load
CO., CHICAGO

TRANSFORMER CONNECTIONS

THREE SINGLE PHASE TRANSFORMERS IN A THREE PHASE CIRCUIT.

In the operation of three phase transmission systems many difficulties are encountered and much can be said regarding the merits and effects of connections of transformers used in changing the voltage. If the three single phase transformers are made by the same company there should be no difficulty in connecting them properly in a three phase circuit. If, however, they are made by different companies there is no way to tell by inspection the polarity of the transformers, and consequently it is an easy matter to make an error in connecting up the transformers. The treatment of this question of three transformers has to deal not only with the three sine waves of e.m.f.'s and currents differing by 120 degrees but with the complex waves formed by the combination of the fundamental and higher harmonics of different amplitude and phase relation. A three phase problem embodies not only phase position but also phase rotation. There is this difference between the three phase and the foregoing single phase combinations; that is, the single phase combination will always have the same phase rotation if the phase position is the same, while the three phase combinations may have the same phase position but a different phase rotation.

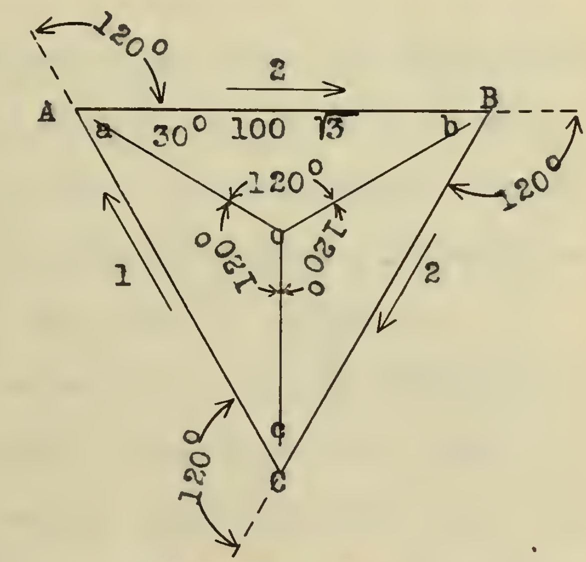


FIGURE 12.

The graphical representation of a three phase circuit

is shown in figure 12. In the three phase circuit there are two types of connections of the coils; the delta shown by the vectors, AB, BC, AC and the Y connection shown by the vectors ao, bo, and co. If we consider these vectors as the fundamental em.f. and current waves then their phase relations are represented diagrammatically by their space position as shown in the foregoing. In passing through the coil windings from (a) to (b) which may be considered the instantaneous direction in which an e.m.f. must be generated to give an e.m.f. on the main (A) to main (B), the winding (a) is passed through in a positive direction and winding (b) in a negative direction. The e. m. f. between (a) and (b) is 30 degrees behind (a) in time phase and its effective value hence is,

$$2 \text{ E} \cos 30^{\circ} = 3 \text{ E}$$

where E is the value of each of the e.m.f.'s (a b and c)

Considering only the fundamental waves in the diagram the e.m.f. between any two leads ab, bc, or ac, is equal to the e.m.f. in each symetrical winding ao, bo, or co multiplied by the square root of three which is derived from the foregoing since 2 cos 30° equals the square root of three.

For the current relation we see from figure 12 that a positive current in main A, is produced by a positive current in vector AC or resultant vector of ao and co, and that a negative current in the winding number two produces a negative current in main A; therefore the instantaneous value of current in the main is vector $I_1 - I_2$ where I_1 and I_2 are the currents in vectors one and two. Similarly the currents in the other mains are the same as the relation in main A. The current in main A is 30 degrees behind vector one hence the effective value of the current in the main A is the square root of three

[illegible]

times the current in a coil in the delta connections.

There are the two methods of connecting the coils of transformers in a three phase circuit, they are the delta and the Y connections. In the balanced delta connection the e.m.f. on the receiving circuit is the same as that on the coils and the current in each receiving circuit is equal to the square root of three times that in the balanced coil. In the Y connection the current in the line and winding are the same while the voltage per phase is equal to the square root of three times the voltage per coil.

To transform three phase alternating current from one voltage to another the following methods may be employed:

1. Three single phase transformers connected in Y or delta.
2. Two single phase transformers connected open delta or T.
3. One three phase transformer connected Y or delta.

There are in general four ways in which three single phase transformers may be connected between primary and secondary in a three phase circuit. These arrangements are described as delta-delta, Y-Y, Y-delta, and delta-Y.

The style of connection best adapted to transmission depends upon the voltage, distribution, and reliability necessary for its operation. In winding transformers for high voltages the Y connection has the advantage of reducing the voltage per coil, thus permitting a reduction of turns and an increase size of the conductors, making the coils easier to wind and insulate.

The delta-delta connection nevertheless has a distinct advantage over the Y-Y or Y-delta arrangement, in that if one transformer of a group of three should become disabled, the two remaining ones will continue to deliver three-phase power with slight unbalancing

due to the different impedances in the middle main and the two out-side mains, the impedance in the middle main being the sum of the impedances in the two out-side mains. When one coil is disabled the combination takes the form of the "V" transformation which will be considered later.

In the Y - Y arrangement as shown in figure 13, each trans-

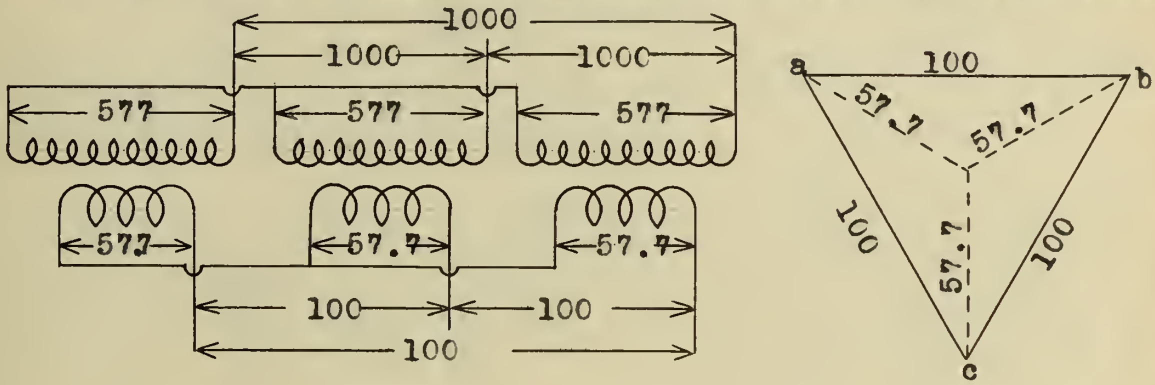


FIGURE 13.

former has one terminal connected to a common junction or neutral point, the three remaining ends are connected the three phase mains.

Figure 14 shows a Y - Y connection in which one of the secondary windings is reversed. It may be noted that the phase relation is changed from 120 degrees to 60 degrees by the reversal of one coil.

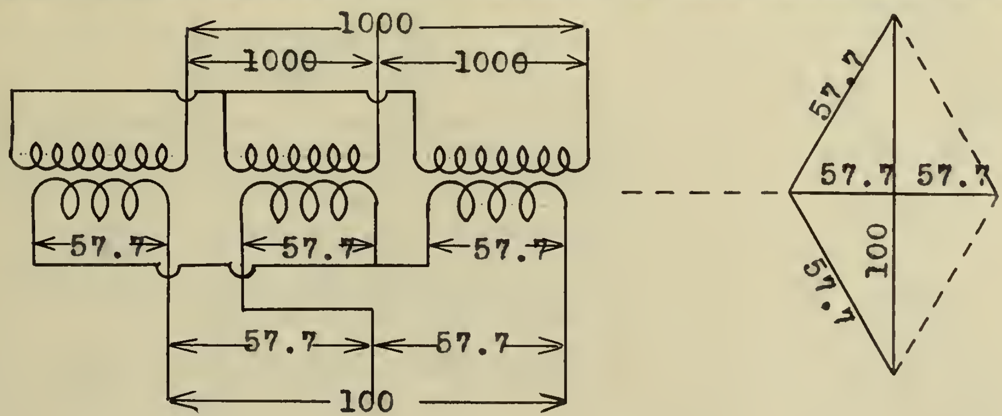


FIGURE 14.

however, the detail analysis of duch conditions will be considered later by use of oscillograms and data.

In the Y - delta connection shown in figure 15 the ratio of transformation is 1/ 3 or .577 times the ratio of secondary to the primary turns and the e.m.f. acting on each secondary is the same as

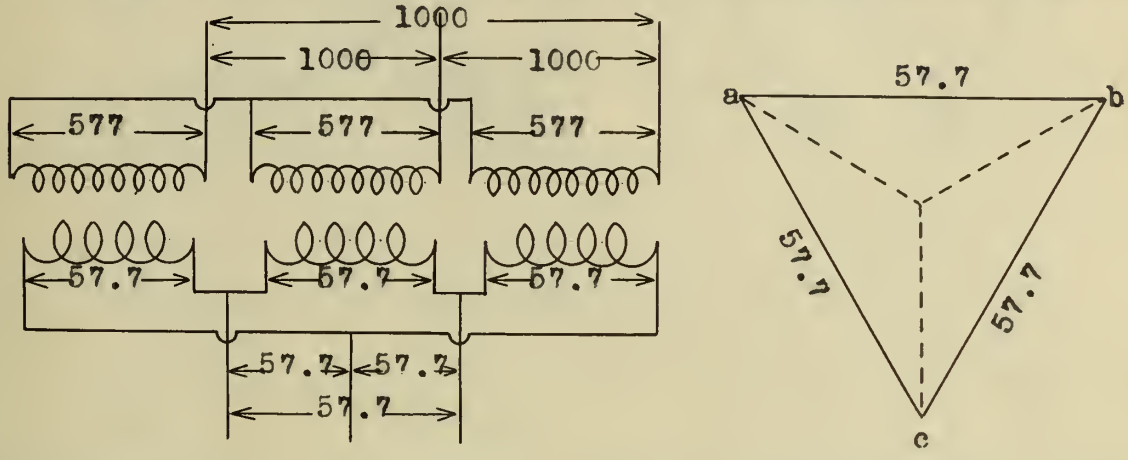


FIGURE 15.

that between the mains.

The delta- Y connection is shown in figure 16 using three single phase transformers. The ratio of transformation for the delta-Y arrangement is the square root of three of 1.73 times the ratio of secondary to primary turns.

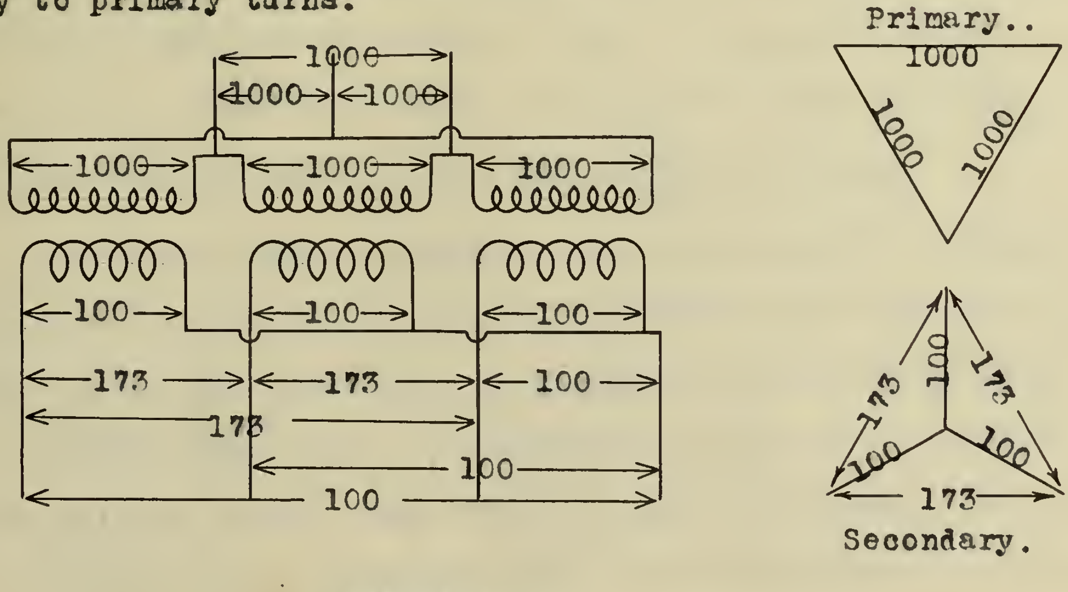


FIGURE 16.

The second method of transformation of three phase current by use of two single phase transformers is commonly called the "V" or open delta connection. The voltages across the open ends of the two transformers is the resultant of the voltages of the other two phases

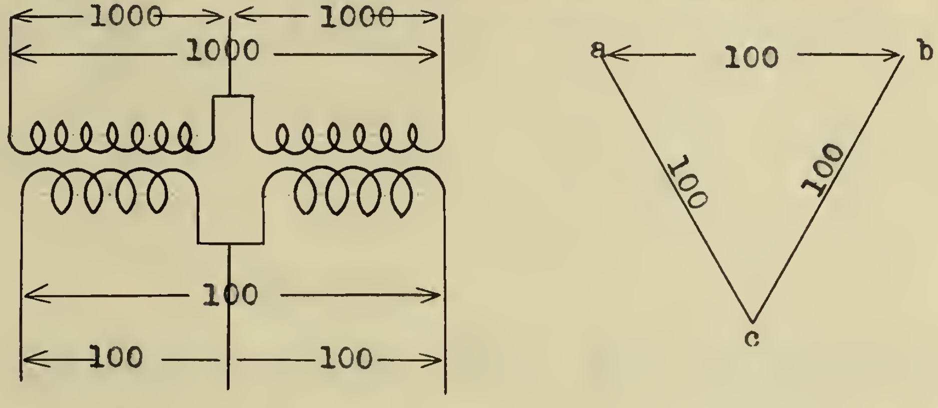


FIGURE 17.

as shown in figure 17. This method requires 16 percent more transformer capacity than any previous three phase transformations shown, based on same efficiency of transformation, heating, and total power transformed. This fact taken alone does not represent a disadvantage for the "V" connection, because the two larger transformers are equal in constructive material and operating efficiency to the three smaller transformers. The real objection to the "V" connection lies in the tendency for the local impedance of the transformers to produce large unbalancing of secondary voltages and primary currents.

A method shown in figure 18 of employing two transformers in a three phase transformation which practically overcomes the disadvantages of the "V" connection and possesses considerable merit is found in the "T" connection. Its ability to maintain balanced phase relations is much better than the open delta arrangement and in many cases it is preferable to either the Y or delta methods of connecting

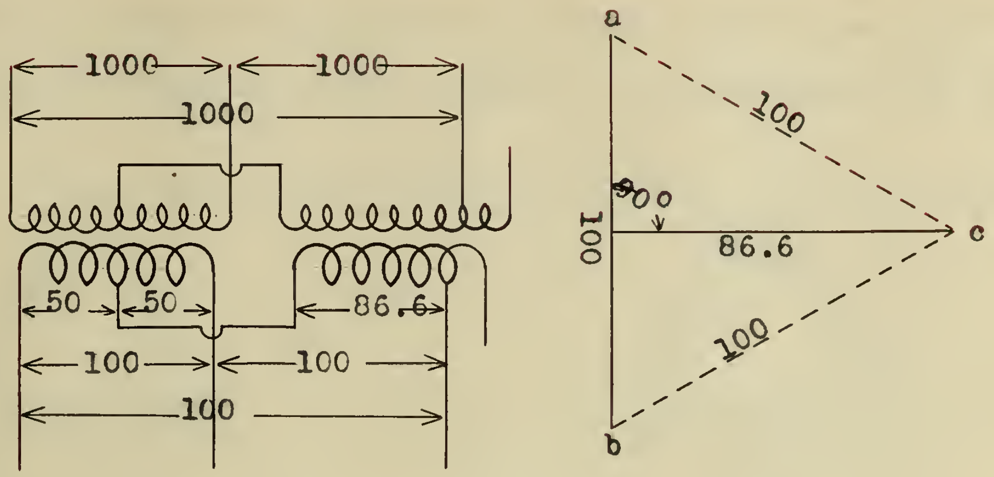


FIGURE 18.

three single phase transformers in a three phase transformation. It is also worthy of note that the voltage impressed across one transformer is only 86.6 percent of that across the other so that if each transformer is designed especially for its work one will have a rating of EI and the other a rating of .866 EI, where I is the current in each line wire and E is the e.m.f. between lines. The combined rating will therefore be 1.866 EI as compared with 1.732 EI for three single phase transformers connected either delta or Y; or with a rating of 1.90 EI for two V connected transformers.

In the operation of three phase transmission systems it is often desired to operate not only the primary but also the secondary of the system in parallel. This gives way to a various number of combinations of Y and delta connections, when three single phase transformers are used for each unit of transformation. However the use of some of these combinations is not permissable due to the fact that they will cause a partial short circuit when the secondaries are put in parallel.

We are now prepared to take up the question as to what

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combinations in parallel operation will cause trouble and which will not give rise to a partial short circuit. To illustrate the point

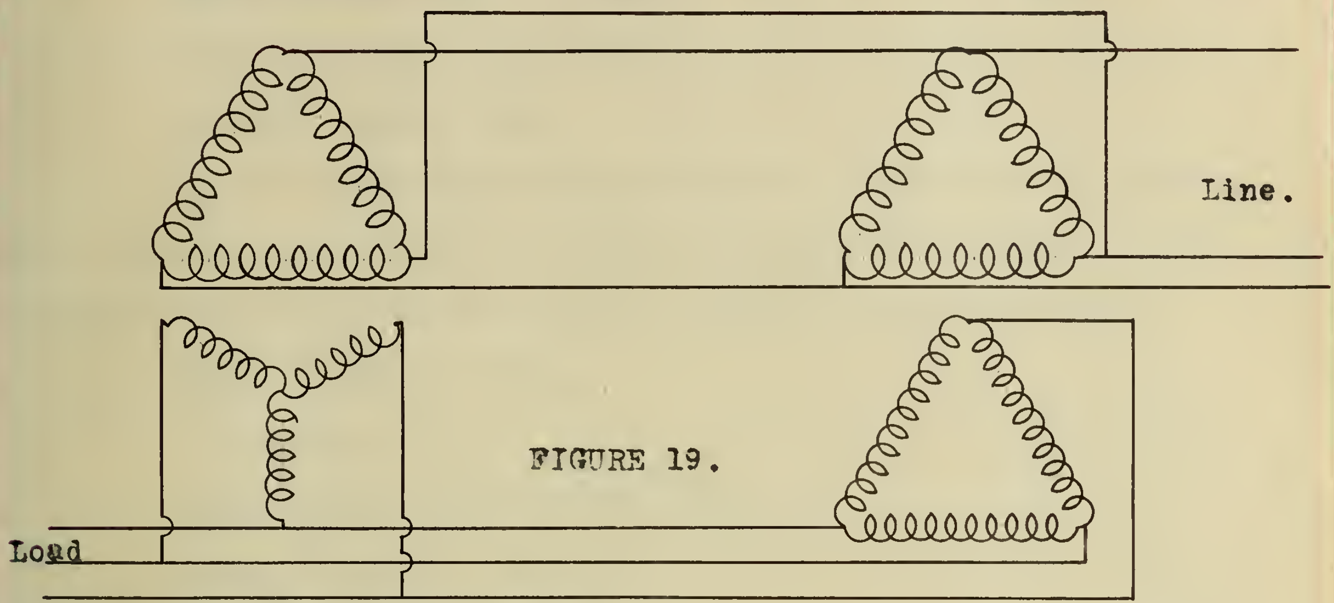
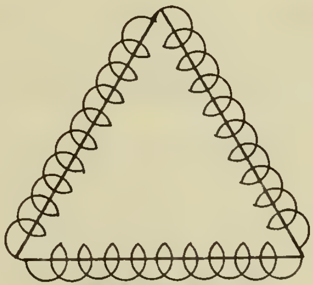
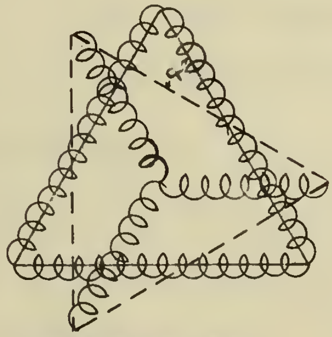


FIGURE 19.

consider the delta-Y combination in parallel with a delta - delta group as shown in figure 19. In order that transformers will operate satisfactorily together the first requirement must be that the voltage transformation is correct. Figure 20 shows the secondaries superimposed upon each other. Keeping in mind parallel operation of secondaries, it is evident that when the secondaries are paralleled the result will be a partial short circuit due to the phase displacement by angle α. Likewise according to the same course



Primary.



Secondaries.

FIGURE 20.

of reasoning the following groups cannot be operated in parallel.

Delta-Y with a Y-Y.

Delta-Delta with a Y-delta.

Delta-Y with a delta-delta.

Y-delta with a Y-Y.

In the following combinations it is possible to get the phase relation and rotation correct and hence with proper voltage, and voltage regulation they will operate together satisfactorily:

Delta Y with a delta Y.

Y Y with a Y Y.

Delta delta with a delta delta.

Delta Y with a Y delta.

Delta delta with a Y Y.

A rule may be quoted here to facilitate the reader in remembering whether or not the foregoing combinations will operate satisfactorily. " In the parallel operation of the primaries and the secondaries of three phase transformation by use of three single phase transformers, the combinations will operate satisfactorily if the symbol △ or Y is contained an even number of times in the combination; taking for granted that the voltage transformation is correct."

In the tests of transformation of three phase power by using three single phase transformers the following units were used:

GENERAL ELECTRIC TRANSFORMERS.

#465423 60 cycle G2, 1200 - 2400/120-240 volts, 1.5 K. W.

#4291295 60 cycle G2, 1200-2400/ 120-240 volts, 1.5 K. W.

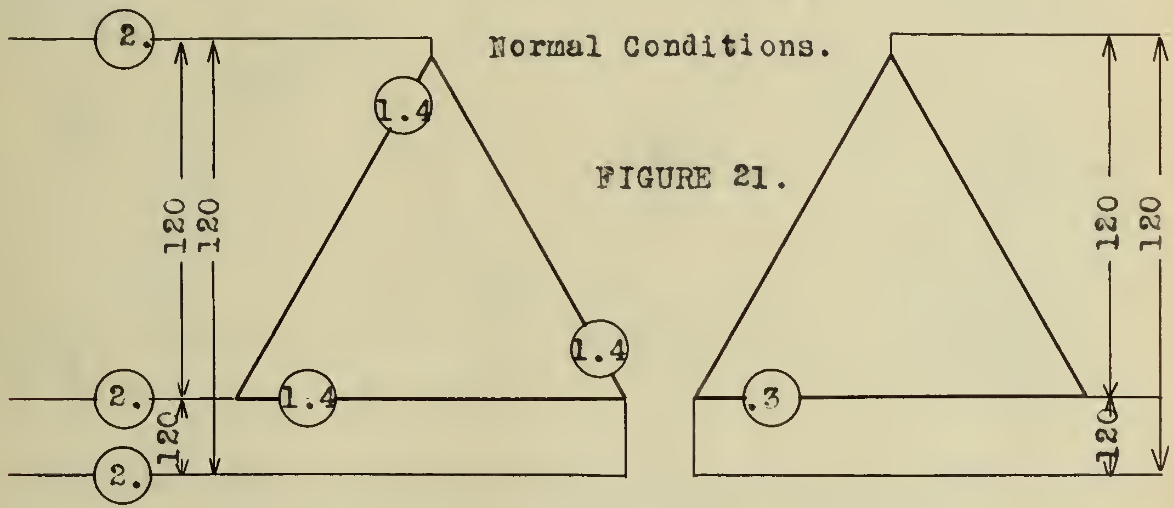
#4652236 60 cycle G2, 1200-2400/ 120-240 volts, 1.5 K. W.

It may be well to state here that in all the tests on three single phase transformers, only the secondary coils were used, thereby

obviating the handling of high voltages. One secondary coil was used as primary and the other coil as secondary. Since it is comparative values of voltages and currents that is to be shown, this method is considered to be satisfactory. There was no load on the secondaries.

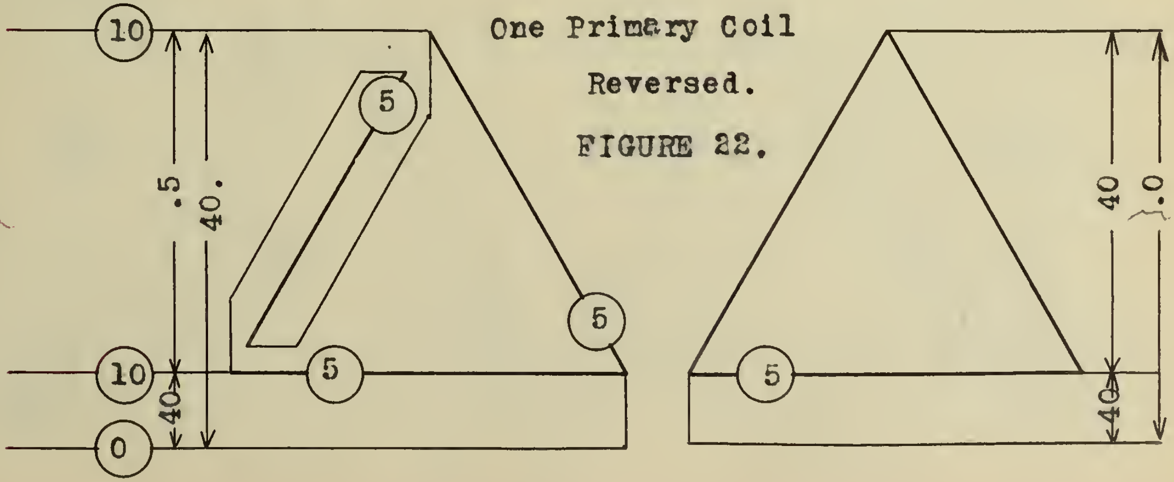
To simplify the explanation the following diagrams of three single phase transformers will represent the primary on the left and the secondary on the right. Also that in all figures which are drawn for the purpose of showing the results of experiment, straight lines will represent coils.

The following figures show the results obtained by opposing different coils and combination of coils:



Normal Conditions.

FIGURE 21.



One Primary Coil Reversed.

FIGURE 22.

FIGURE 23, One Secondary Coil Reversed In The Delta Delta Group.

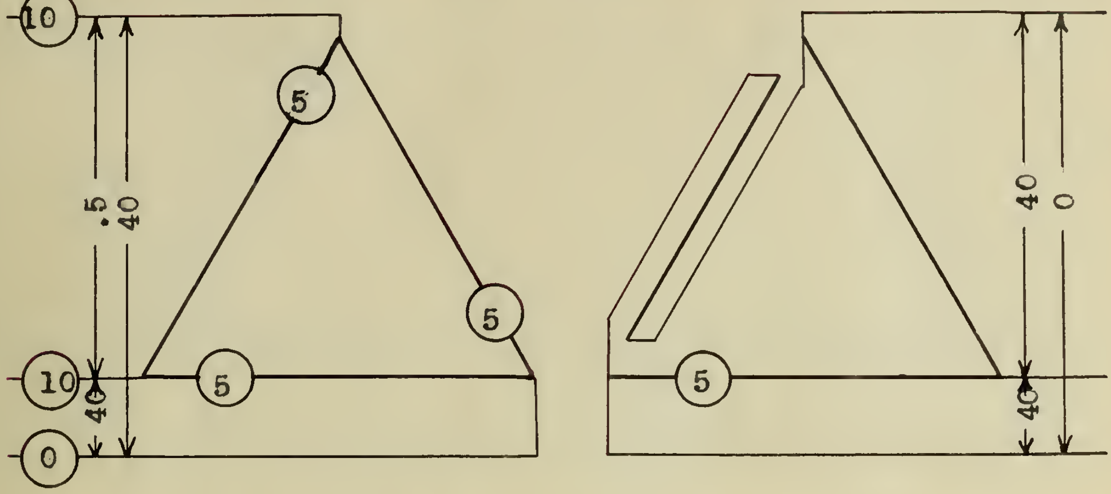


FIGURE 24, One Primary and Corresponding Secondary Coil Reversed.

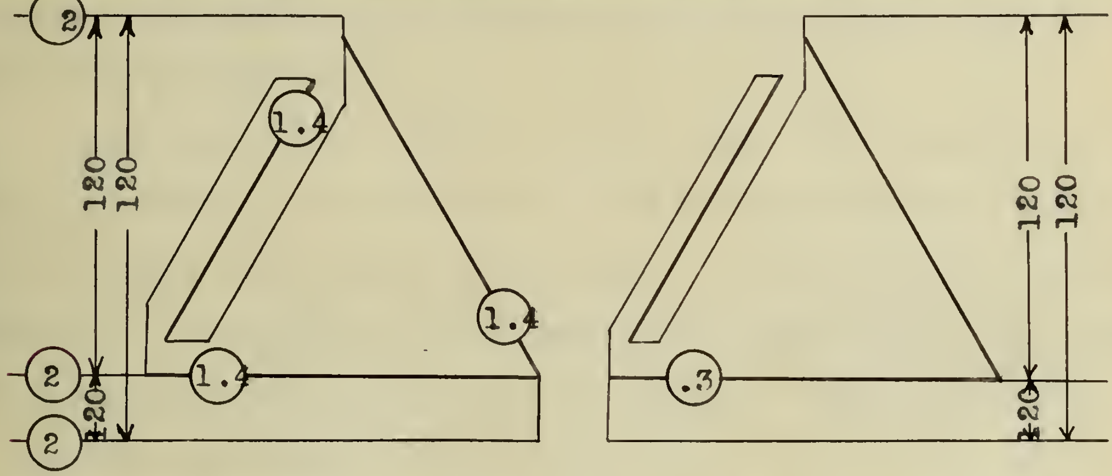


FIGURE 25, One Primary and Noncorresponding Secondary Coil Reversed.

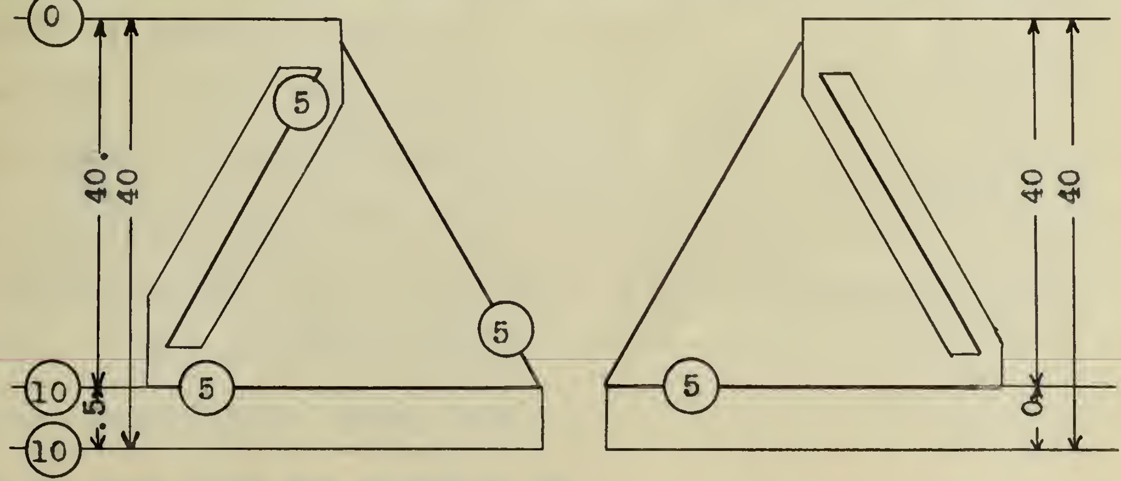
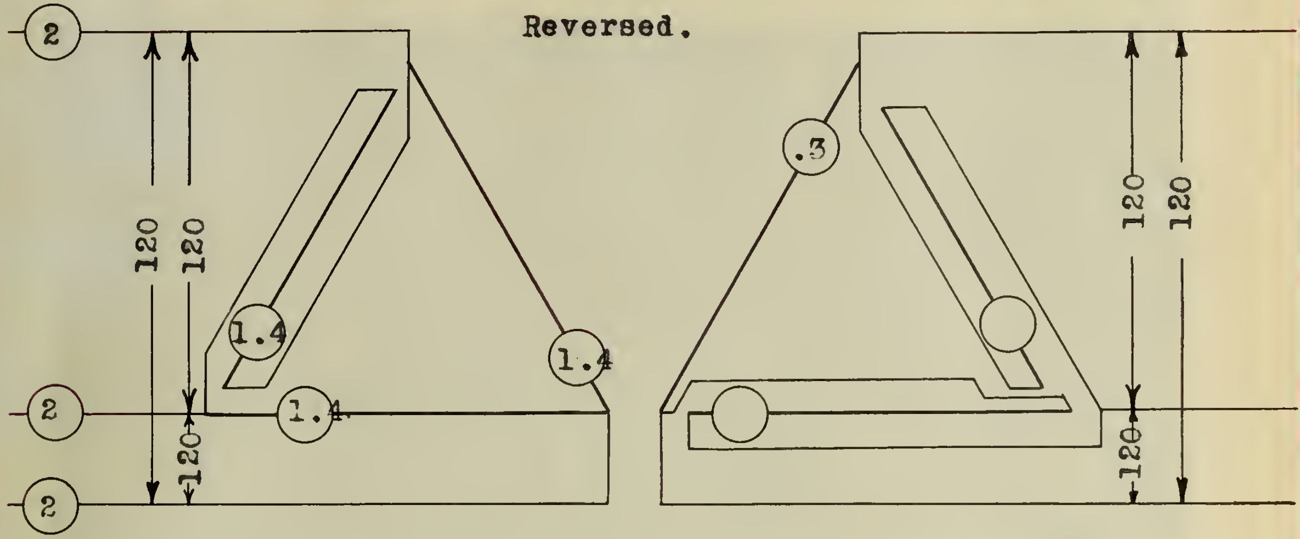


FIGURE 26, One Primary and Two Non-corresponding Secondary coils Reversed.



In the cases where coils are reversed it becomes necessary to impress a very much lower voltage per coil in order that the current may not be excessive.

From the foregoing data on the delta delta connections the following conditions were obtained. If any one primary or secondary coil is reversed the voltage across that coil and also its corresponding secondary or primary will be practically zero, while the voltage across the coils not reversed will be normal. This may readily shown from the collasped voltage condition of the three phase triangle, as shown in figure 27. The current in line three, which comes from the junction of the two normal coils, is very small, while the current in the other two lines is large. The currents in the coils are practically same, but it may be seen from the relation in

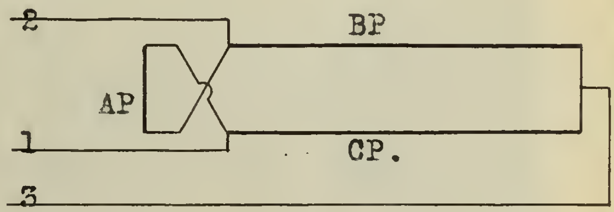
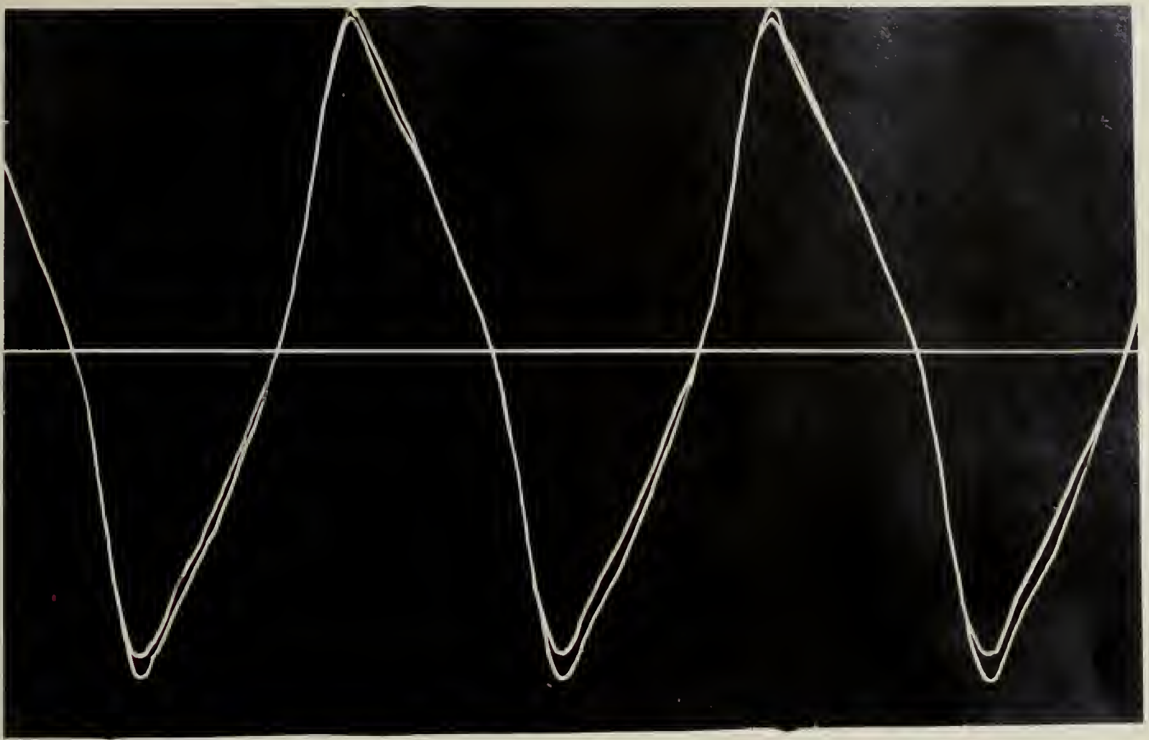


FIGURE 27.

FIGURE 28, Oscillograms for Line Current with one coil Reversed in a Three Phase Circuit With Three Single Phase Transformers.



The above is for the Delta-Delta Connection.

FIGURE 29, Oscillograms for Voltage with One Coil Reversed in delta delta connection of 3 ø Circuit with Three Single Phase Transformers.

the oscillogram figure 28, taken of the currents, that the coils AP and BP of figure 27 have currents, two of which are in phase, while the third is zero. Likewise the oscillogram figure 29, shows that there are two voltages almost in phase and the third is out of phase about 180 degrees.

It is observed from the data that when a low voltage is impressed upon the transformers and one coil is reversed, that on opening one corner of the delta a voltage about twice the coil voltage is obtained. Since the transformer is worked at a low density with this lower impressed voltage, then the higher harmonics are not present to a large extent. Since, therefore, the harmonics are not present, then the fundamental will be as shown in figure 30. This is, therefore, always a good test to be made before bringing up the voltage to normal and closing the delta, in order to be sure that all the coils are connected together in their proper order.

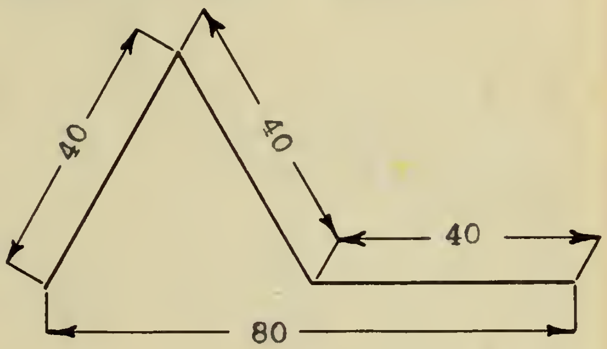


FIGURE 30.

When any primary coil and a corresponding secondary coil of this delta delta combination are reversed at the same time the conditions bring themselves back to the normal condition again. This is what would be expected, since it is the opposing of the primary or secondary coil with respect to the other that gives the reversed conditions. If, however, a primary and non-corresponding secondary coils are reversed the conditions are the same as if only one coil was reversed. This may be explained from the fact that reversing two coils still keeps them in the same phase relation but in so doing

the phase relation of the third coil is reversed. If in the delta delta connection as before any three non-corresponding primary or secondary coils are reversed the conditions are brought back to normal, as seen from the reasoning above. This is what could be expected, since reversing two coils acts like opposing one coil, then if we reverse this third coil we must have all three coils in their proper phase relation again.

Next consider the results of reversing different coils and combination of coils with the Y- secondary and Y primary.

FIGURE 31, Normal Condition Of Y - Secondary and Y - Primary.

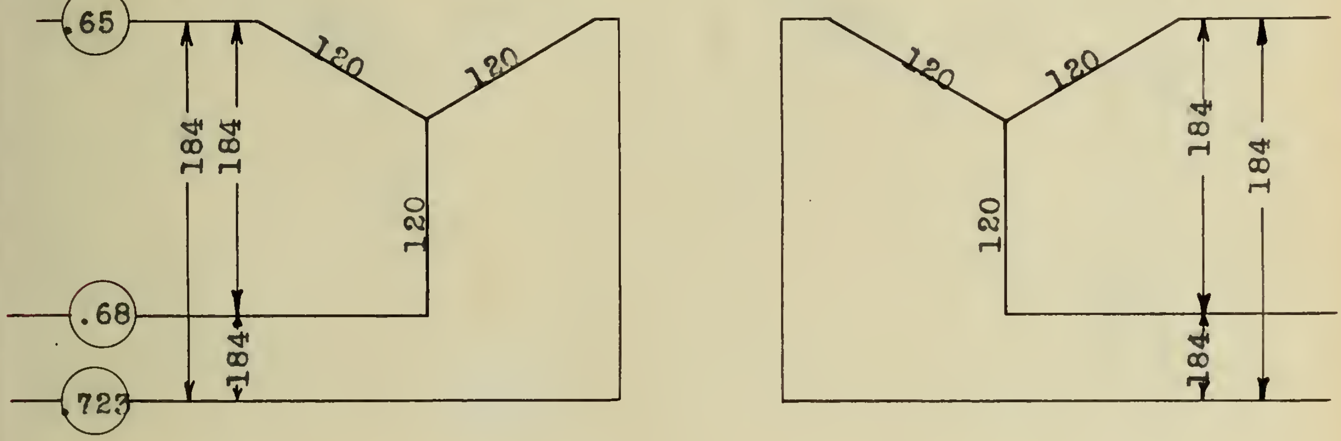


FIGURE 32, One Primary Coil Reversed of the Y - Y Connection.

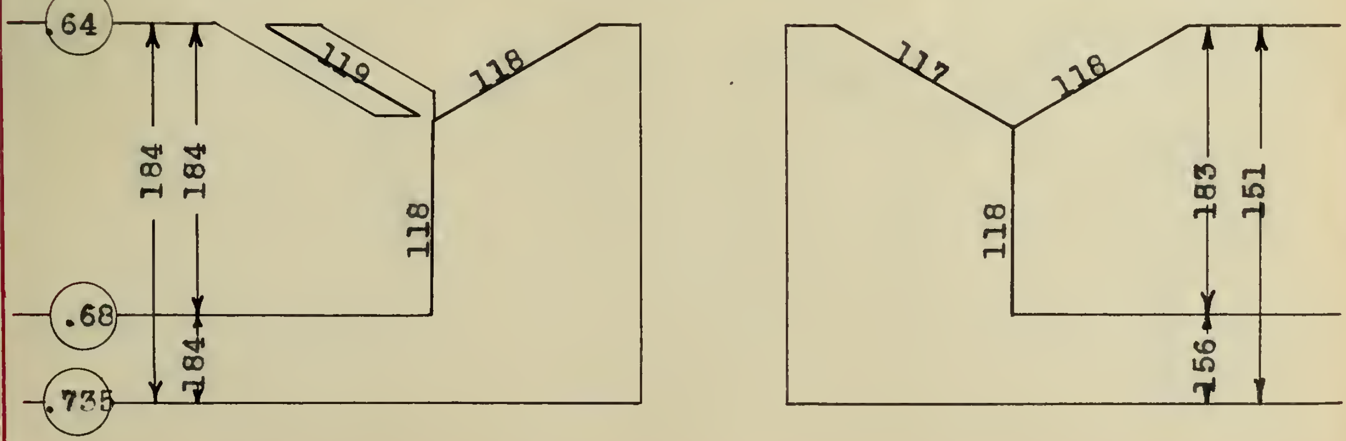


FIGURE 33, One Secondary Coil Reversed.

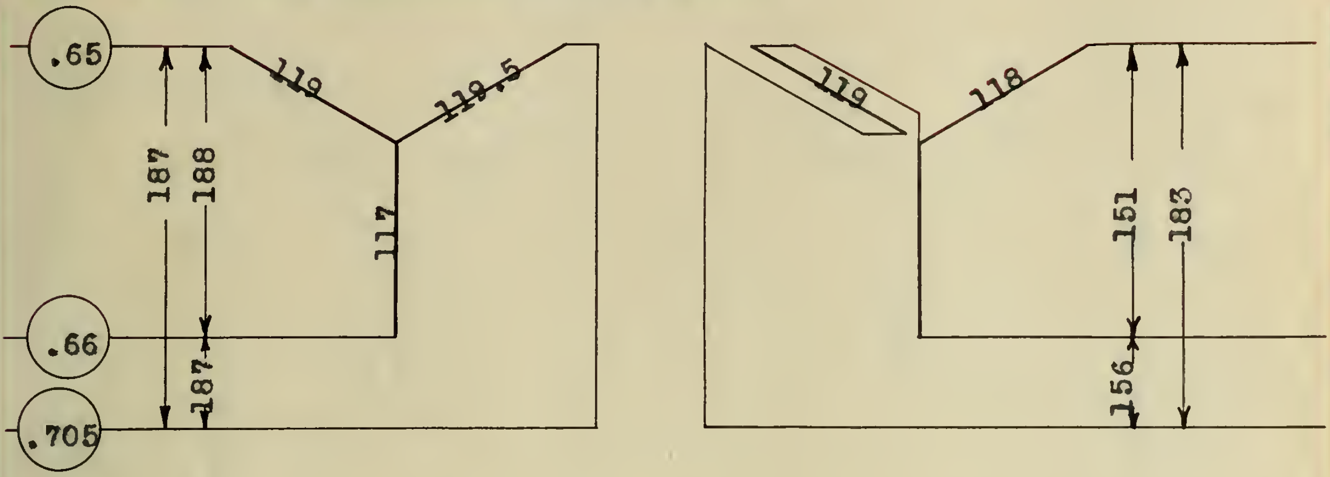


FIGURE 34, One Primary and Corresponding Secondary Coil Reversed.

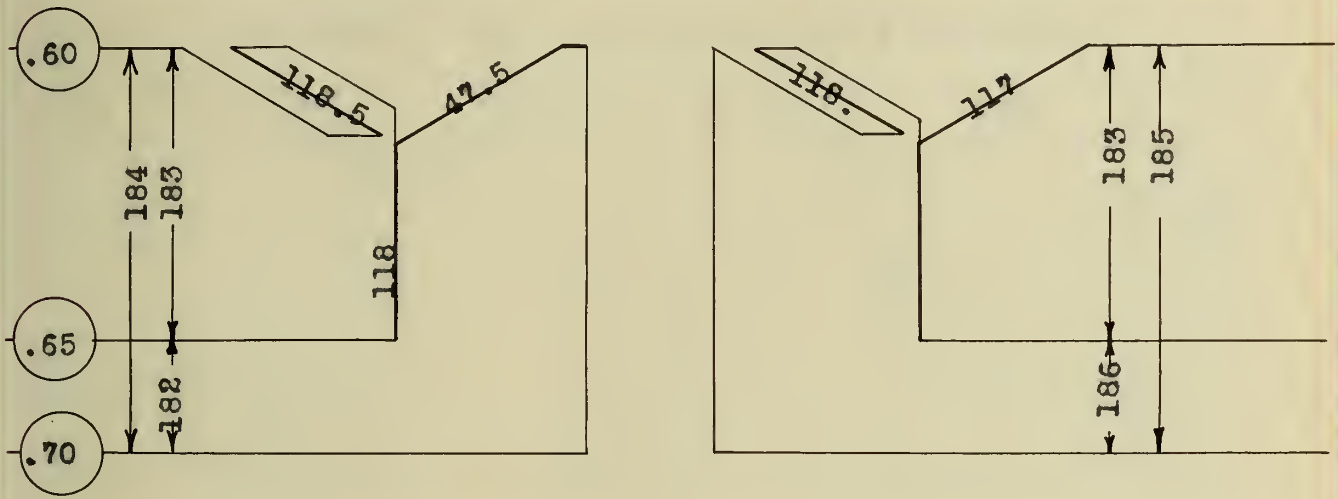


FIGURE 35, One Primary and a Non-corresponding Secondary Reversed.

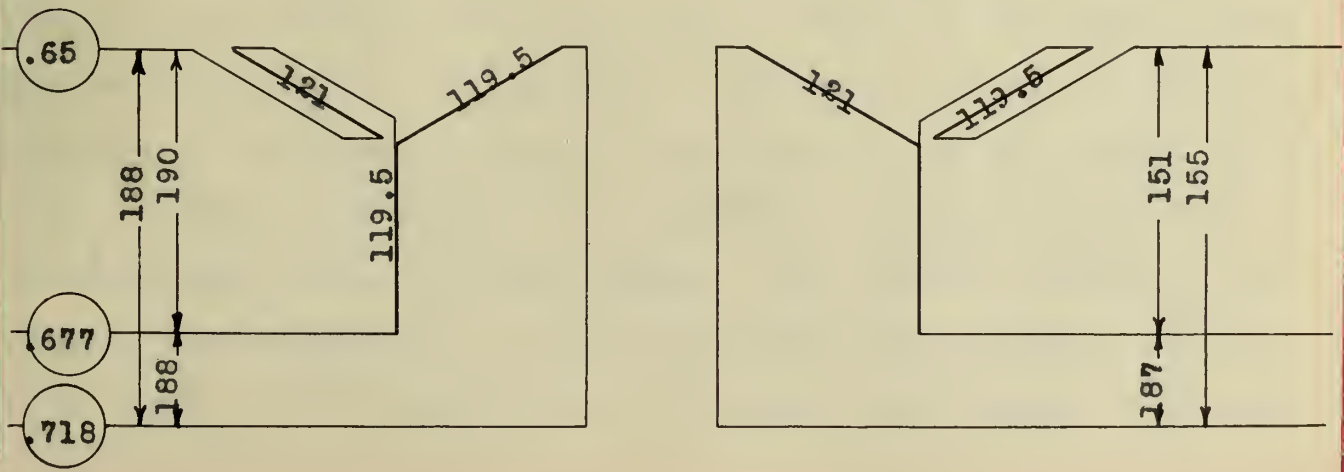


Figure 36, Two Primary Coils Reversed.

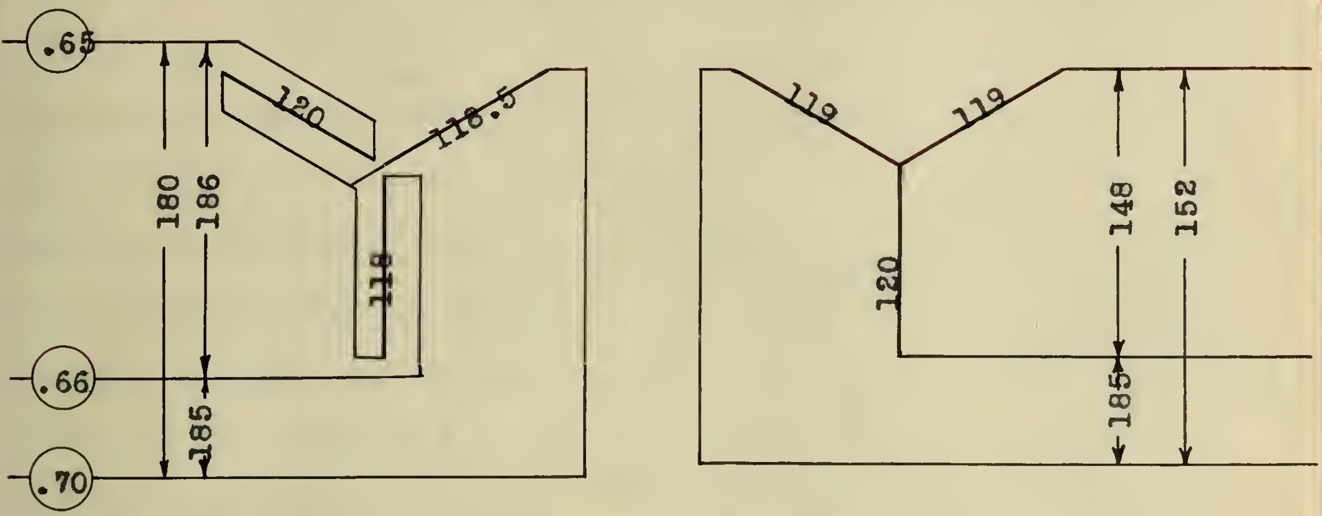
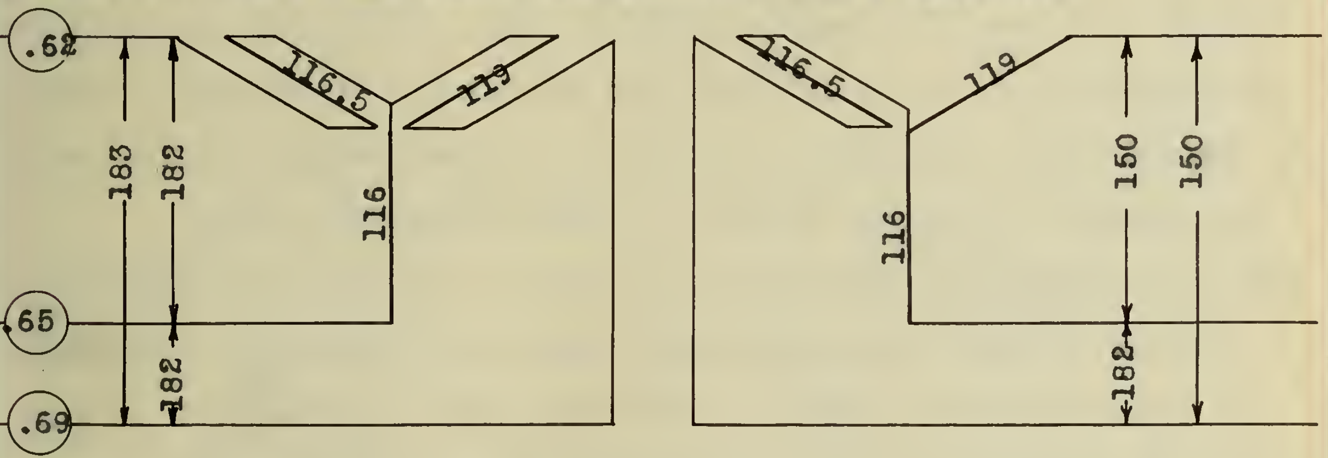


Figure 37, Two Primary and one Secondary Coils reversed.



From the data obtained for the Y - Y connections the following conclusions may be derived. With the transformers correctly connected the voltage across each coil is equal to the line voltage divided by the square root of three plus the triple of the coil as measured. The current in each coil is the same as the current in the line. When a primary coil is reversed the voltages across the primary lines and coils remain normal. The current likewise is the same in this connection, as is the secondary coil voltage, but the error shows in the reading of the secondary line voltage. The line

voltage across the two coils not reversed remains normal, while the voltage from the coil reversed to either of the other coils has a lower value, thus giving two small values and one normal value of the secondary line voltage. This can be easily shown by figure 38. The voltage between the secondary lines B' and C' remains normal, since B'O and C'O remain in the same phase relation to each other. The voltages between A'C' and B'A' becomes smaller than normal due to the new phase relation of 60 degrees, in place of 120 degrees, between the reversed coil and either normal coil.

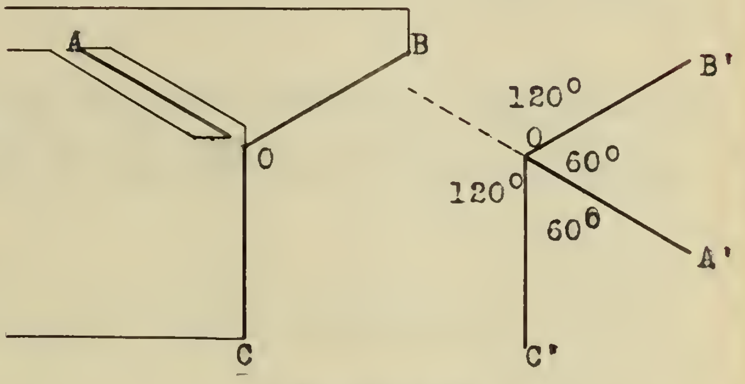


FIGURE 38.

When a secondary coil is reversed in the Y-Y connection, the results are the same as when the corresponding primary coil was reversed. Reversing the primary coil causes the flux to thread through the secondary 180 degrees out of phase with its normal direction. This result can be accomplished also by keeping the primary coil normal and reversing the corresponding secondary coil. If two primary coils are reversed the result is the same as keeping two normal and reversing the third, which follows directly from the geometrical relation. When a primary and corresponding secondary coil are reversed it is evident from the foregoing that the conditions are brought back to normal. Reversing two primary coils is the same as reversing one primary and a non-corresponding secondary coil since, from the above reasoning, it was seen that reversing a primary coil was equivalent to reversing the corresponding secondary coil.

Next consider three single phase transformers with their primary Y and secondary delta connected. In these combinations the corresponding primary and secondary coils are drawn with two corresponding coils parallel, the third pair being at right angles to each other.

The following diagrams show the results of reversing the different coils and combination of coils in the Y delta connection, and will be considered later.

FIGURE 39, Normal Conditions of Y delta combination.

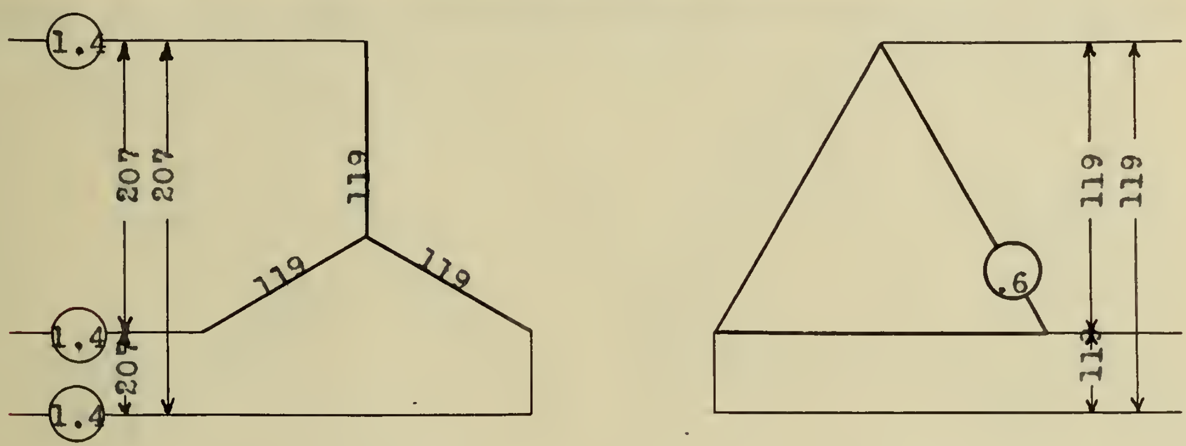


FIGURE 40, One Primary Coil Reversed.

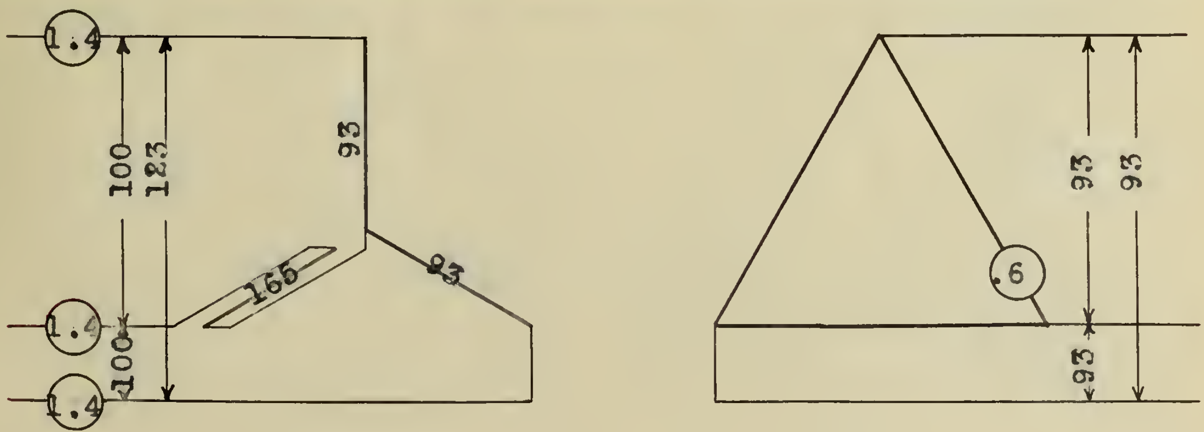


FIGURE 41, One Secondary Coil Reversed in the Y delta combination.

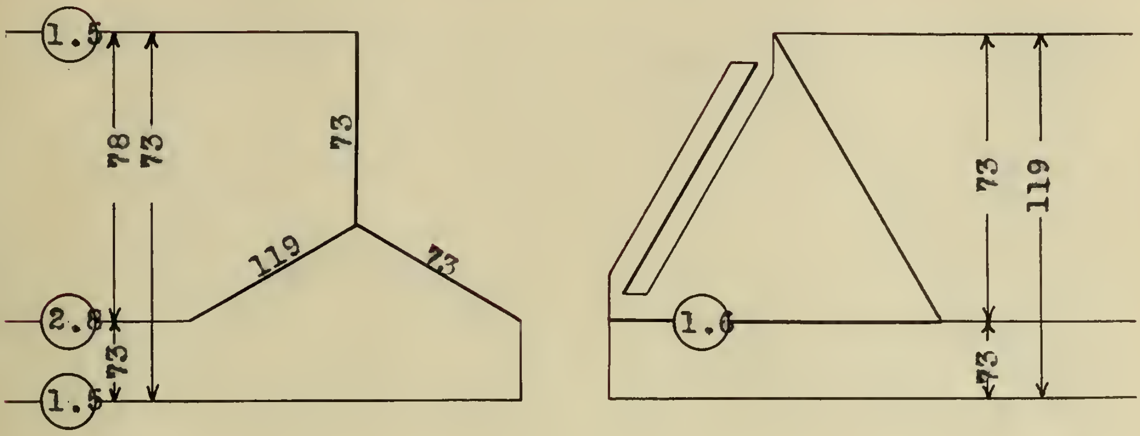


FIGURE 42, One Primary and Corresponding Secondary Coil Reversed.

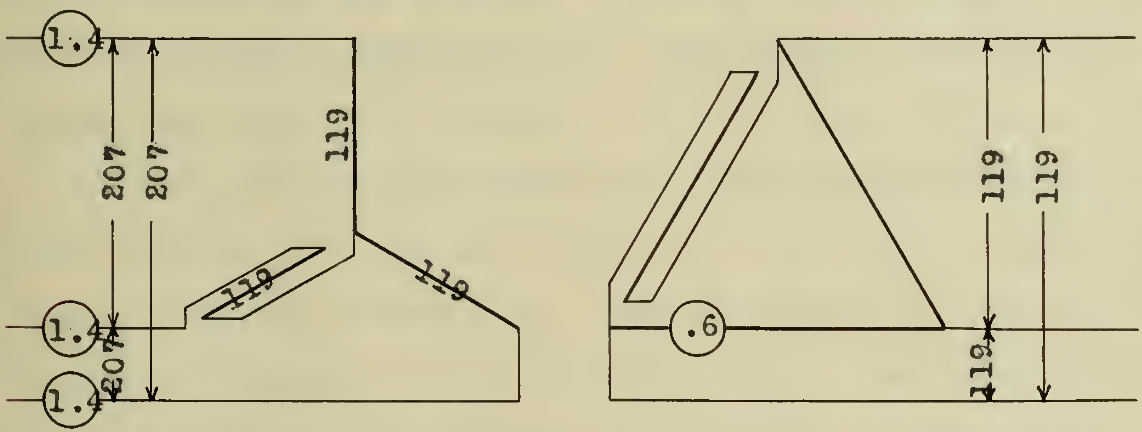


FIGURE 43, Two Primary and Noncorresponding Secondary Coil Reversed.

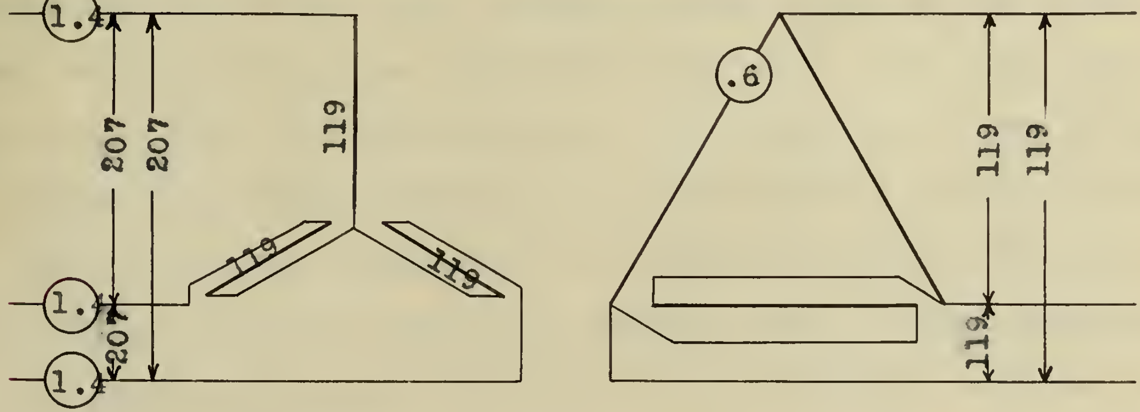
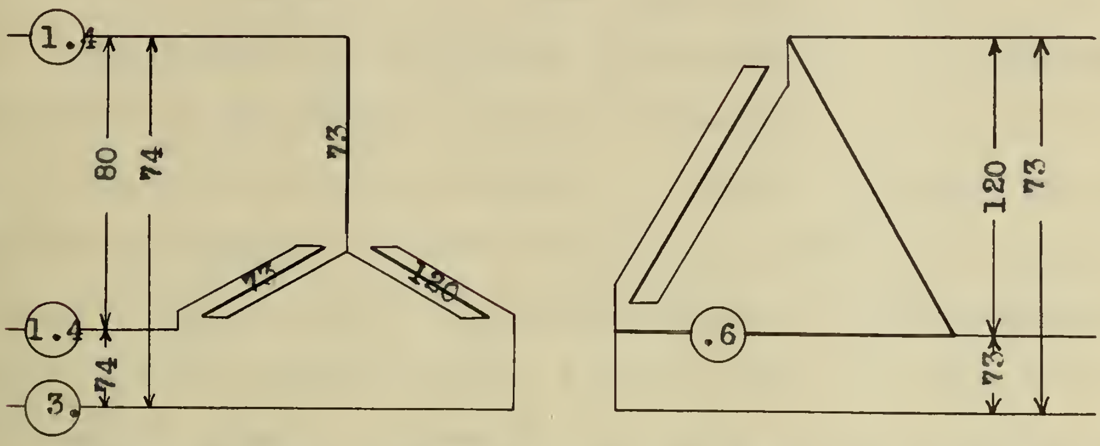


FIGURE 44, Two Primary and Corresponding Secondary Coils Reversed.



From the data obtained for the Y delta connections the following conclusions may be drawn. With the transformers correctly connected the voltage impressed across each primary line is equal to that across the coils time the square root of three. When a primary coil is reversed the voltage between the lines leading from the two good coils remains practically normal while the voltage between the line leading from the reversed coil and the other two lines drop down to about 80 percent of the original value. The voltage across the primary coil reversed is about 1.8 times the voltage of either of the two normal coil voltages. The secondary coil voltages are all the same and of a value equal to that across either of the normal primary coils. It must be remembered that these tests were made with a one to one ratio of transformation. The condition of one primary coil reversed is further shown by the fact that the current in the line leading from the opposed coil is practically twice the value of current in either of the other two primary lines. When a secondary coil is reversed the same ratio exists in line voltages and also between primary coil voltages. The secondary coil voltages are no longer balanced when one primary coil was reversed, but instead the voltage

the voltage across the two normal coils are balanced,while the voltage across the coil reversed is 1.6 times that across either of the normal coils. The current in the primary line leading to the primary coil corresponding to the secondary that is reversed is twice the value of either of the other two line currents. In case a primary coil and a corresponding secondary coil are reversed the conditions become normal. This is also true if any two primary coils and a non-corresponding secondary coil are reversed due to the fact that althrough each coil is reversed 180 degrees, in reality the phase relation between them remains the same, for three are reversed.

Next consider three single phase transformers in a three phase circuit with their primary delta and secondary Y connected. The following diagrams show the results of reversing different coils and combination of coils.

FIGURE 45, Normal Conditions of Delta Y connection.

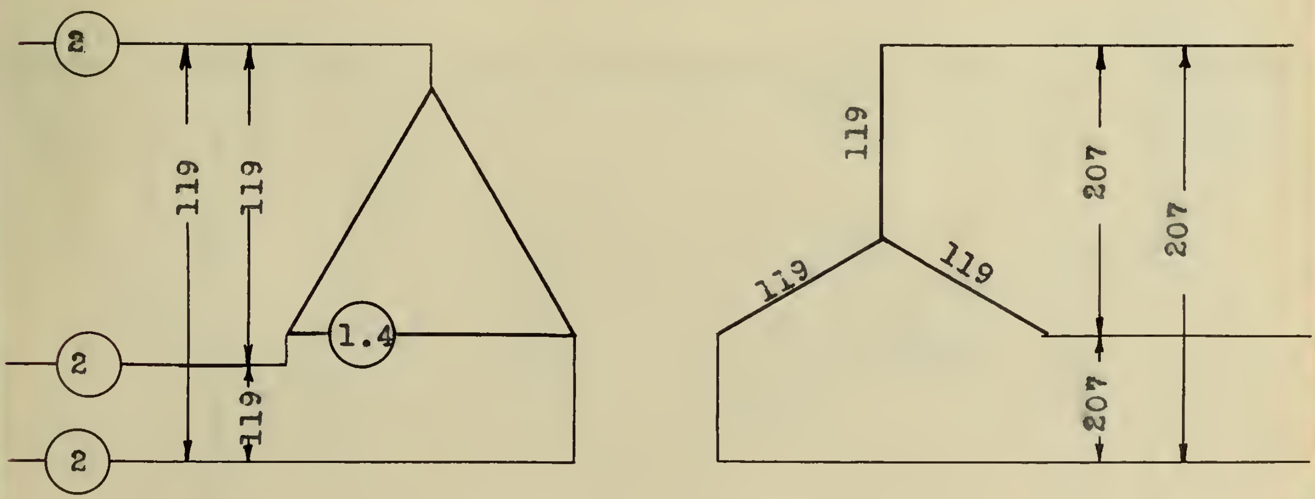


FIGURE 46, One Primary Coil Reversed in the Delta Y Combination.

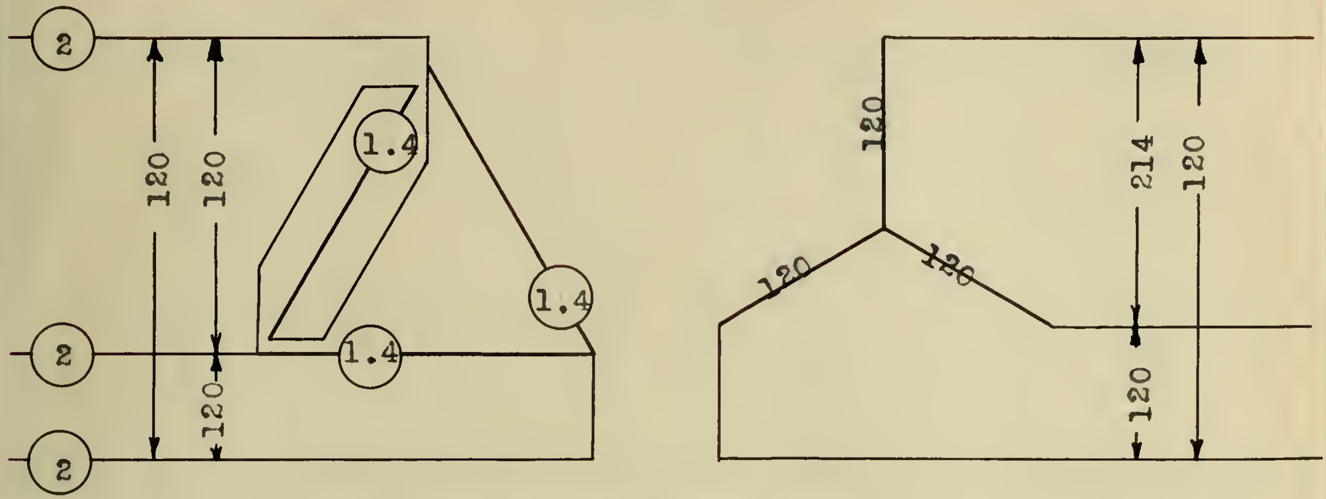


FIGURE 47, One Primary and Corresponding Secondary Coil Reversed.

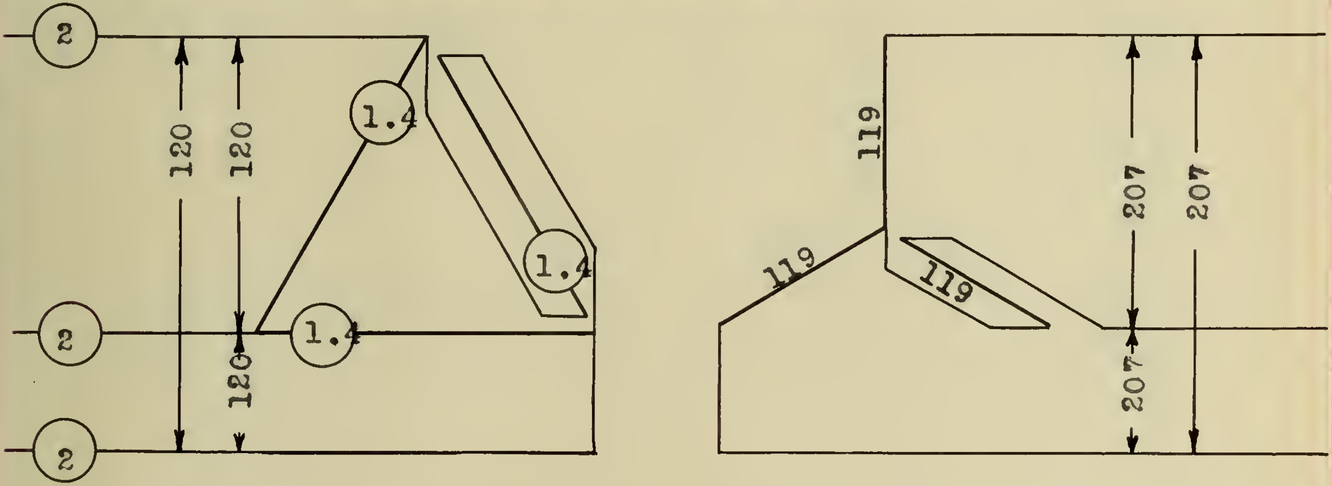


FIGURE 48, One Primary and Noncorresponding Secondary Coil Reversed.

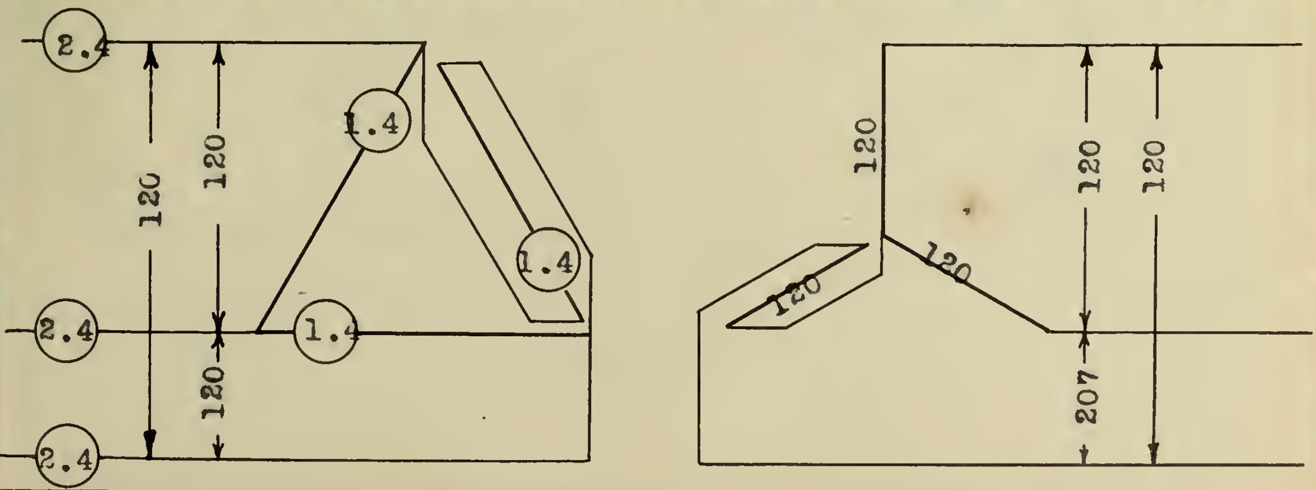


FIGURE 49, Two Secondary and One Noncorresponding Primary Coil Reversed.

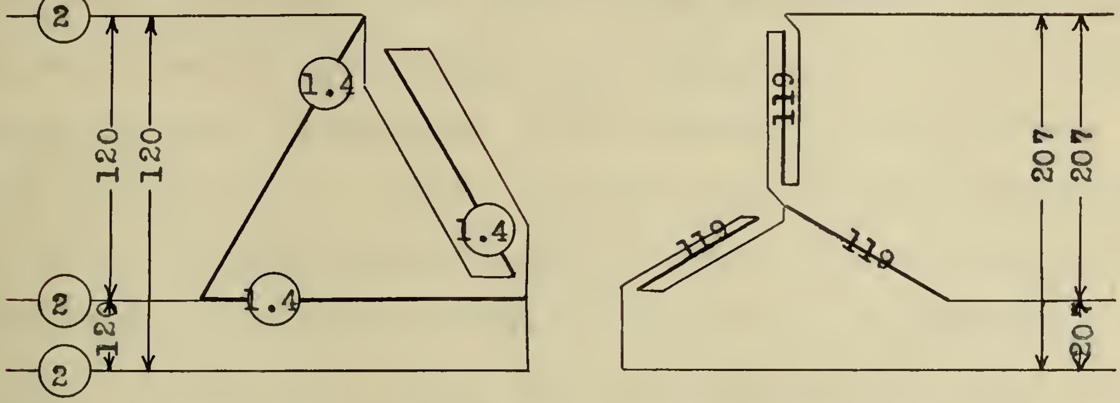
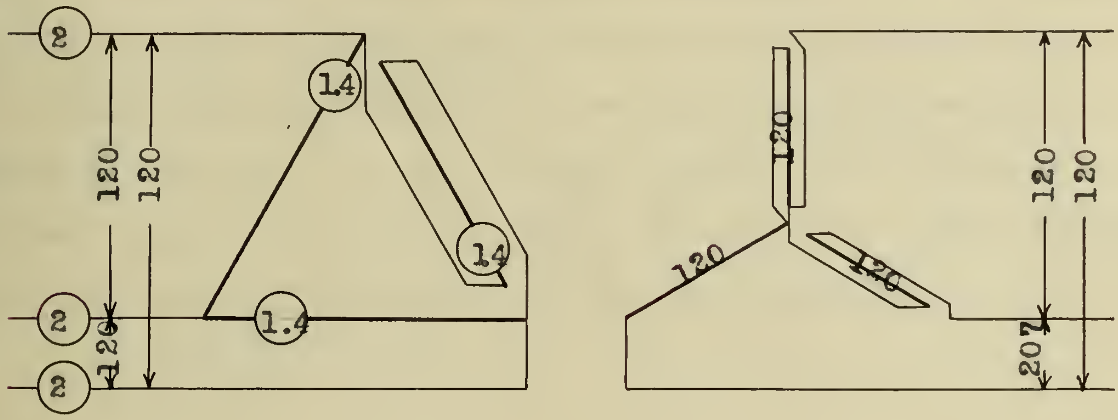


FIGURE 50, Two Secondary and One Corresponding Primary Coil Reversed.



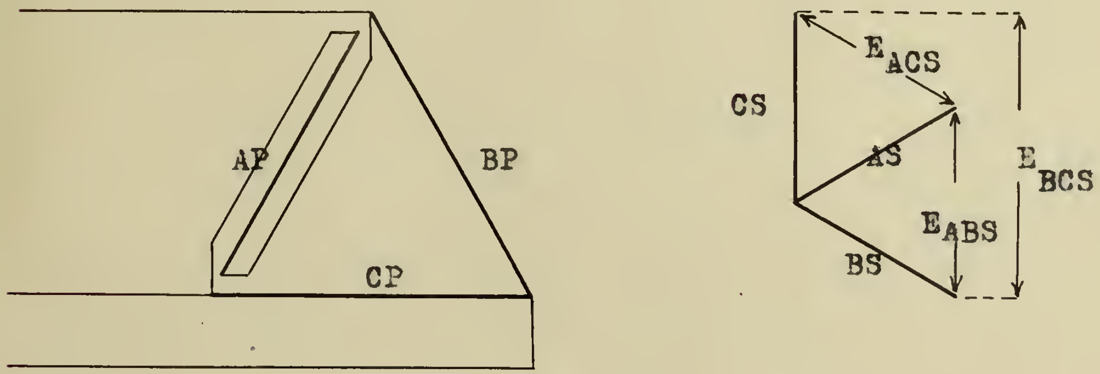


FIGURE 51.

From the observed data for the delta Y connection we may determine the following conditions. When one primary coil is reversed the voltages across both primary and secondary coils remain normal, the existing error being shown by the secondary line voltages. The voltage between the two normal coils was found to be normal, while that between the one reversed coil and either of the normal coils was found to be the normal voltage of each coil, as shown in figure 51. Reversing a primary coil and a corresponding secondary coil brings the conditions back to normal, since there is no change in phase relation between the voltages. When a secondary coil is opposed the effect is the same as reversing the corresponding primary coil. In the case where two secondary and a non-corresponding primary coil are reversed the result is to keep things normal. This is due to the fact that changing the phase relation of all three coils 180 degrees, brings them back to same phase relation with each other.

SUMMARY OF INVESTIGATION
OF CONNECTION OF THREE SINGLE PHASE TRANSFORMERS
IN A THREE PHASE CIRCUIT.

There were twenty five different connections investigated and while certain conclusions have been drawn from the results obtained it has not been possible to explain in detail why the observed voltages and currents should exist with certain connections. An attempt is here made to summarize the results as regards the voltage and the current effect.

FIRST:- FROM VOLTAGE CONDITIONS.

1. WITH TWO LARGE VOLTAGES AND ONE SMALL VOLTAGE.

a. If small voltage is zero or practically zero on both the secondary and primary it indicates the connections are delta - delta and that the low voltage is across the reversed coil.

b. If the small voltage has an appreciable value on the secondary side and the primary voltages are only slightly distorted, then the connections are delta Y with one leg of the delta reversed, the highest secondary voltage being between the terminals of the two good coils.

2. WITH ONE LARGE AND TWO SMALL VOLTAGES.

a. If this condition is found to exist on the primary side as well as on the secondary the transformers are connected Y delta with one leg of either primary or secondary reversed. The large primary voltage will be across the terminals of the two good coils while the largest secondary voltage will naturally be across the reversed coil. While the two small primary voltages are equal, the

two small secondary voltages may not be equal.

b. If there exists one large and two small voltages on the secondary side only, the primary voltages being equal, then the connections may be either delta Y with one secondary coil reversed, or Y-Y with either a primary or secondary coil reversed. In any case the large voltage will be between the terminals of the two good coils.

SECOND:- FROM CURRENT CONDITIONS.

1. WITH ZERO CURRENT IN ONE LINE.

a. The connections are delta delta with one leg reversed.

2. WITH TWO LARGE AND ONE SMALL (not zero) CURRENTS.

a. The connections are delta Y with one leg reversed. If it is the primary coil that is reversed the small current goes in one corner of the delta next to the reversed coil. If it is the secondary coil that is reversed the small current goes in the corner of the delta opposite the reversed leg.

3. WITH ONE LARGE AND TWO SMALL CURRENTS.

The connections are Y delta with one leg reversed. The large current goes into the transformer whose leg is reversed,be it either primary or secondary coil.

The connections in any of the above cases may be rectified by changing either the secondary or the primary of the reversed coil.

TRANSFORMER CONNECTIONS

THREE PHASE TRANSFORMERS IN A THREE PHASE CIRCUIT.

In the consideration of the three phase transformer there are two types to be dealt with; namely, the core type and the shell type. Figure 52 shows diagrammatically the construction of the three phase core type transformer. Figure 52-A shows a figure which readily illustrates the flux conditions in the three phase core type of transformer. The core type has practically no triple frequency voltage because the three triple frequency fluxes are in the phase relation that they neutralize each other as seen in figure 52-A.

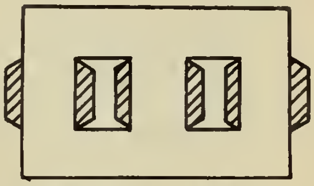


FIGURE 52.

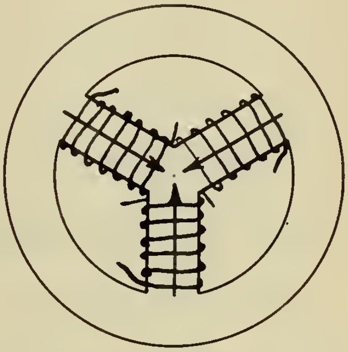


FIGURE 52A.

The shell type three phase transformer is shown diagrammatically in figure 53. Figure 53-A shows a figure which readily illustrates the flux conditions in the three phase shell type transformer. The shell type transformer has usually a greater triple voltage than the core type, due to the phase relation of the three triples. The oscillograms show that there are present the higher harmonics in the shell type transformer.

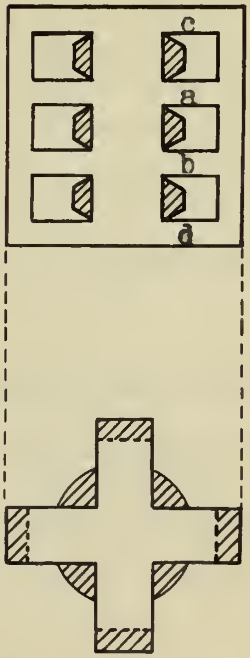


FIGURE 53.

In the three phase core type, the

cross section of each main core corresponding to the flux necessary to give the counter e.m.f. of one phase, but there might be some question about the proportions of the various magnetic paths. As shown in figure 54, the resultant of two coil e.m.f.s is always the same as each individual coil e.m.f., hence, the main cores and connecting bars will have the same flux and, therefore, should be the same cross-section.

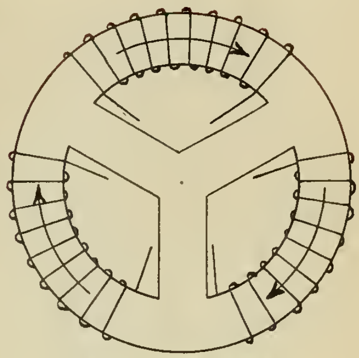


FIGURE 53A.

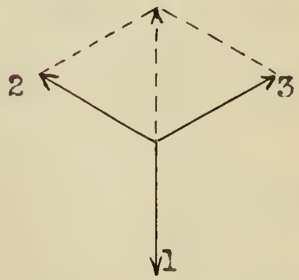


FIGURE 54.

A three phase shell type transformer can be considered as three single phase transformers built one upon the other. The connecting bars make either two or four parallel paths for the flux, depending upon the number of connecting bars. In the case the shell type transformer did not have the middle coil reversed, the flux in each connecting bar such as (a) or (b) in figure 53 would have to be $\frac{\sqrt{3}}{4}$. If, however, the winding of the middle section is reversed, as shown in Figure 54, then the resultant flux in (a) or (b) must be due to e.m.f.'s 1-2 and 1-3, or since there are four parallel paths the flux in the connecting bars must be one fourth of the flux in the main core.

In the tests which were run for this part of the consideration, two three phase transformers, one a shell type and the other a core type, were used. Both transformers were of same rating made by the General Electric Company:

The core loss data showed the following data when normal voltage and frequency was impressed.

CORE LOSS CORE TYPE.

	I_1	W_1	I_2	W_2	Watts
	2.75	210	2.3	-118	
	2.74	205	2.22	-116	
Average,	2.745	207.5	2.26	-117	90.5

CORE LOSS SHELL TYPE

	I_1	W_1	I_2	W_2	Watts
Average,	8.76	580	6.	-455	125

CORE LOSS PARALLEL OPERATION

OF

CORE AND SHEEL TYPE.

	I_1	W_1	I_2	W_2	WATTS
Average,	11.8	795	8.23	-580	215

Check, 90.5 + 125 = 215.5

Now passing to the consideration of the effect of reversed coils, open lines, and open delta, which will be explained by the use of the following data:

Figure 55, shows the voltage relations in the core type transformer when the line A is open, when the transformer is connected in delta delta. As in the discussion of three single phase transformers the coils will be shown by rather heavy black lines and

the low side of the transformer is shown on the left hand side of the sheet, while the high side is shown on the right side of the sheet. In this case, with line A open, it will be seen from the voltage triangle that both the primary and secondary collapsed. This

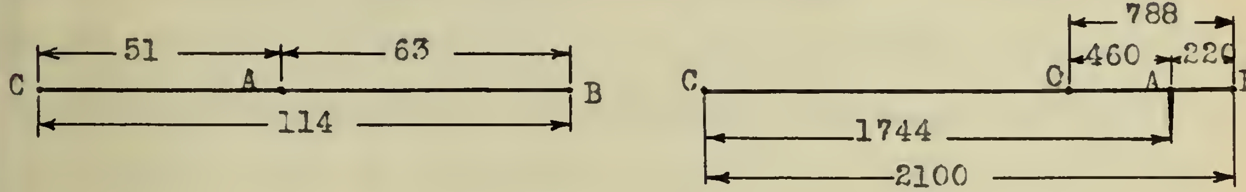


FIGURE 55.

is evident when we consider that there must be no resultant voltage, or in other words the figure must be closed, therefore, since voltage CB is equal to CA plus AB they must be on a straight line. This is because in opening a line there exists only one phase. The same results were obtained when any other line was opened.

The currents likewise collapsed, the smallest current being in the coil having the largest voltage across it, namely BC.

We will next consider the effect of reversing the middle coil of a three phase core type transformer when connected in delta delta. Figure 56, then, shows the voltage triangle when the middle coil is reversed of a core type transformer when connected in delta delta.

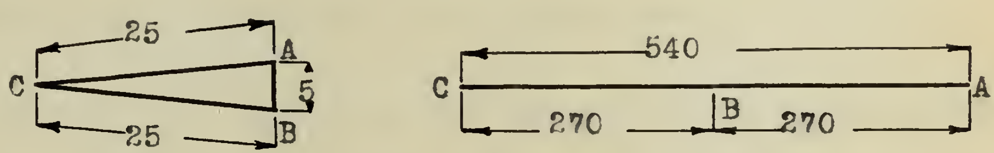


FIGURE 56.

In this condition it will be observed that the secondary voltage triangle collapsed while the primary did not quite collapse.

There are two large values of current leading into the reversed coil, the reversed coil taking more current than the other two coils.

If any line is opened, while one coil is reversed,the strained condition no longer exists, as would be expressed for then only one phase is connected to the transformer. If one of the outside coils is reversed instead of the middle one the results that are obtained are similar to the foregoing case when the middle coil was reversed, with the exception that now the flux from the other coil will pass through the middle leg, hence there will be zero voltage across the reversed coil.

The characteristics of the Core Type transformers is brought out very clearly by inspection of the oscillograms. Figure 57, shows the oscillogram taken for this core type transformer under normal operating conditions. It will be noticed that the triple frequency in the open delta is very small and that the voltage per coil is nearly a sine wave. The triple frequency current is shown in figure 58,together with the voltage per coil. It will also be noticed that the closed delta current is very small as compared with the foregoing results on the three single phase transformers. The open delta voltage,as shown in the oscillogram,is 2.5 volts for the three phase core type while with the three single phase transformers the open delta voltage was 172 volts. This points out a marked difference in the characteristics of these types of transformers.

The shell type transformer,as before explained,is an outgrowth of the core type transformer. The cost of building a shell type transformer seems to be some what cheaper than the core type. This seems to be the only reason for the use of them in place of the

FIGURE 57, Oscillogram showing the Triple Frequency Voltage and the Voltage across the coil for a 3 ∅ Core Type Transformer.

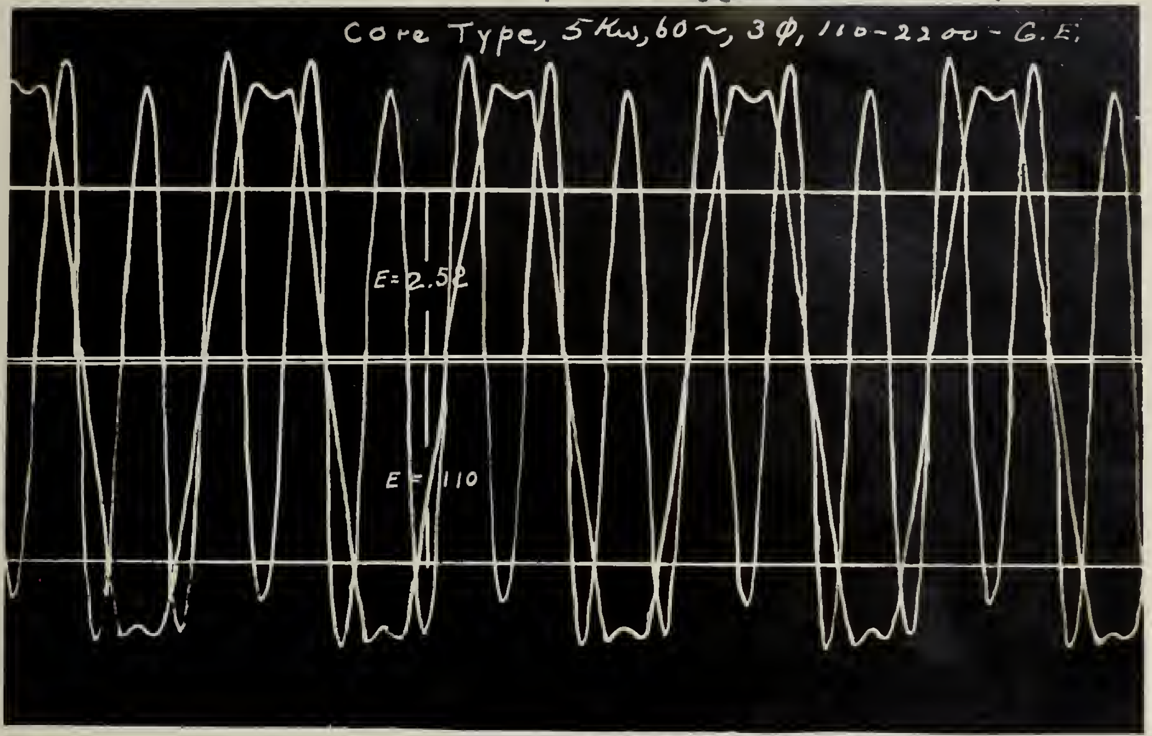


FIGURE 58, Oscillogram showing the Triple Frequency Current in the Delta and Voltage Across the coil for a 3 ∅ Core Type Transformer.

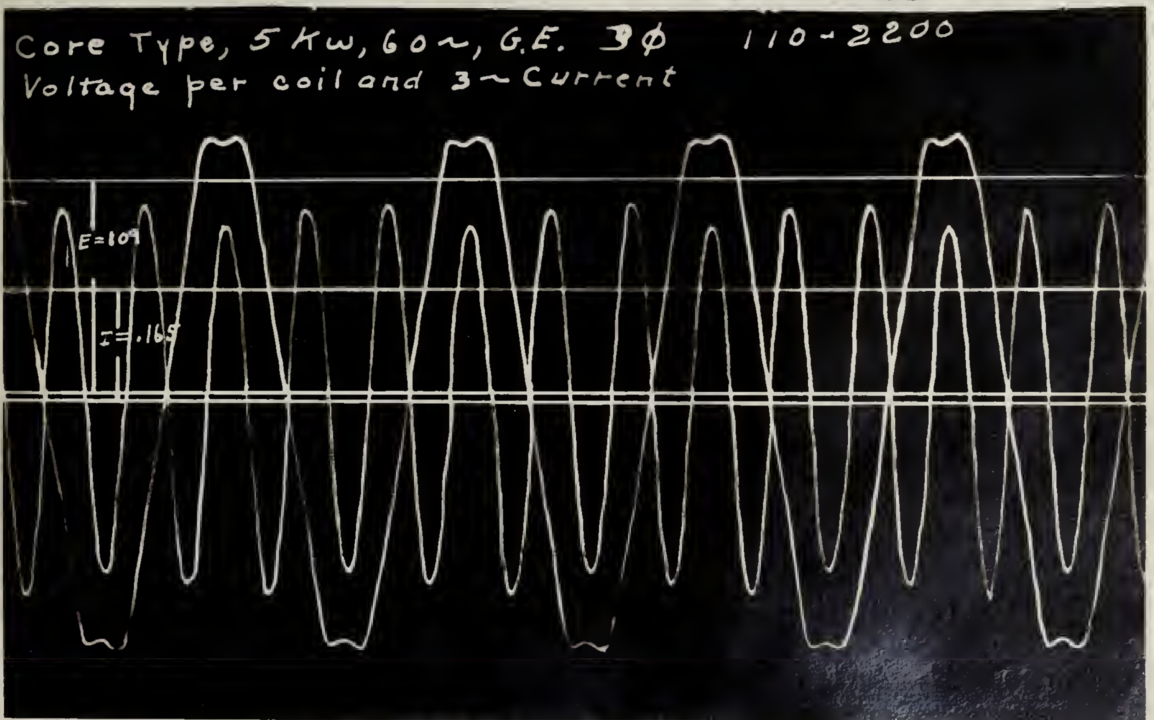


FIGURE 59, Oscillogram of Coil and Line Voltage In Y Connected 3 ∅ Shell Type Transformer.

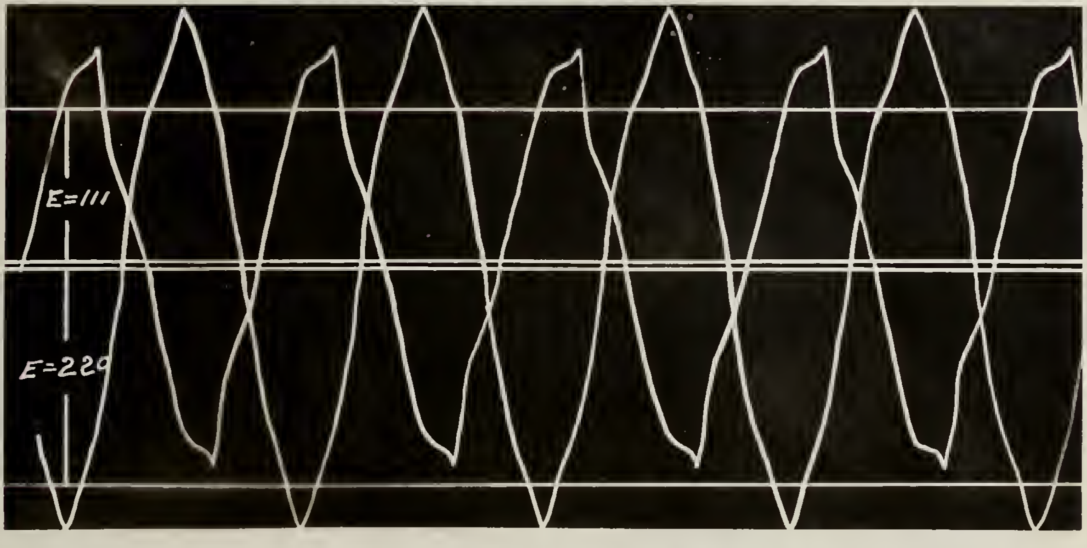


FIGURE 60, Oscillogram of Fundamental and Triple Voltages in the 3 ∅ Shell Type Transformer.

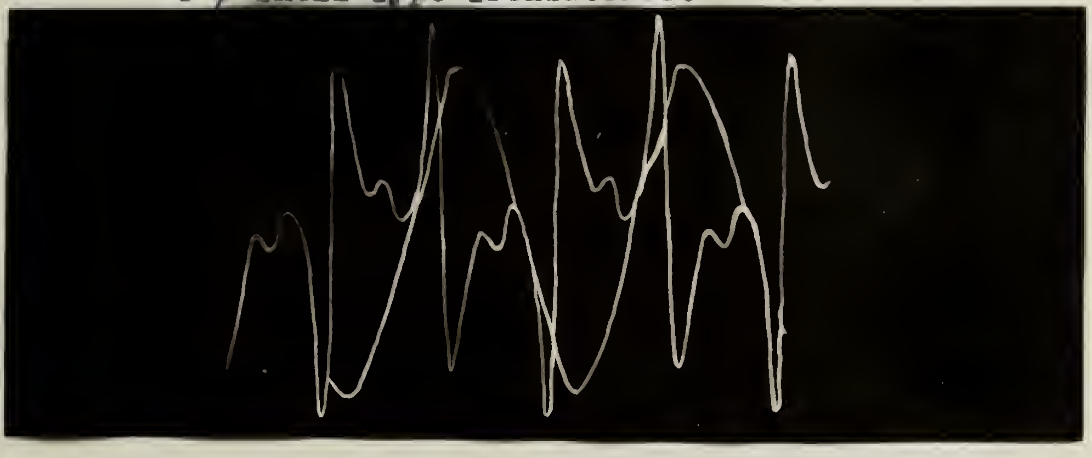
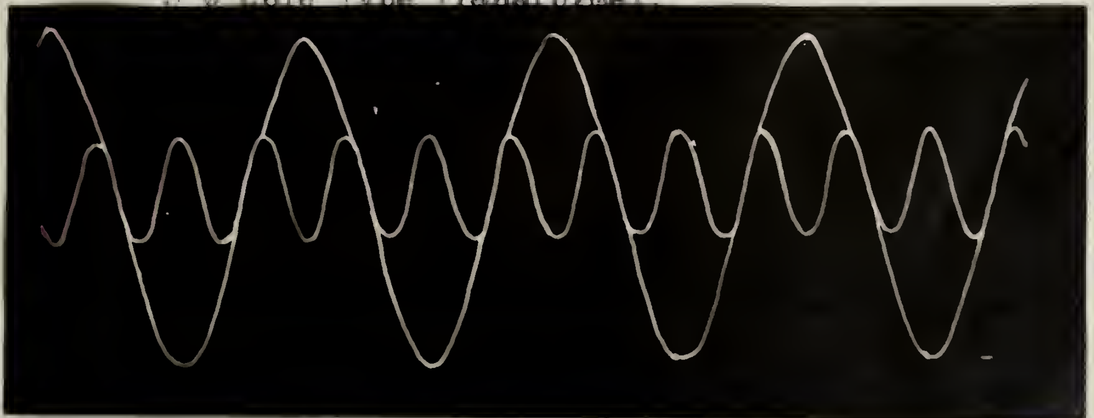


FIGURE 61, Oscillogram of Fundamental and Triple Voltages in the 3 ∅ Core Type Transformer.



Core Type Transformer,which has the small triple voltage and current when compared to the three single phase transformers and also when compared to the shell type.

Figure 60 and 61 show the marked difference in the triple voltages between the core type and shell type transformer. It is evident from the shape of the curve that besides the triple there is prominent higher harmonics present in the shell type.

Figure 62 shows diagrammatically the voltage conditions of a three phase shell type transformer with its primary connected in delta, with line B open.

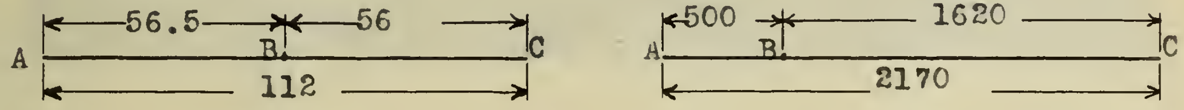


FIGURE 62.

From inspection of the above voltages it is evident that the voltage triangle collapsed as we found before in the core type. The currents also collapsed in a similar manner in the core type transformer

In opening the various lines it was found that if a line was opened such that the impressed voltage was normal across the middle coil in the shell type the other voltages were equal and one half of the normal voltage. This condition is due to the fact that there are equal flux paths, while normal voltage is impressed upon an end coil there are two parallel flux paths of different reluctance, giving a higher voltage to the middle coil than to the opposite end coil.

Figure 63 shows the voltage diagram for the condition of reversing a coil in the shell type with primary connected delta and

FIGURE 64, Oscillogram for Line Current with One Coil Reversed in a 3 ∅ Shell Type Transformer.

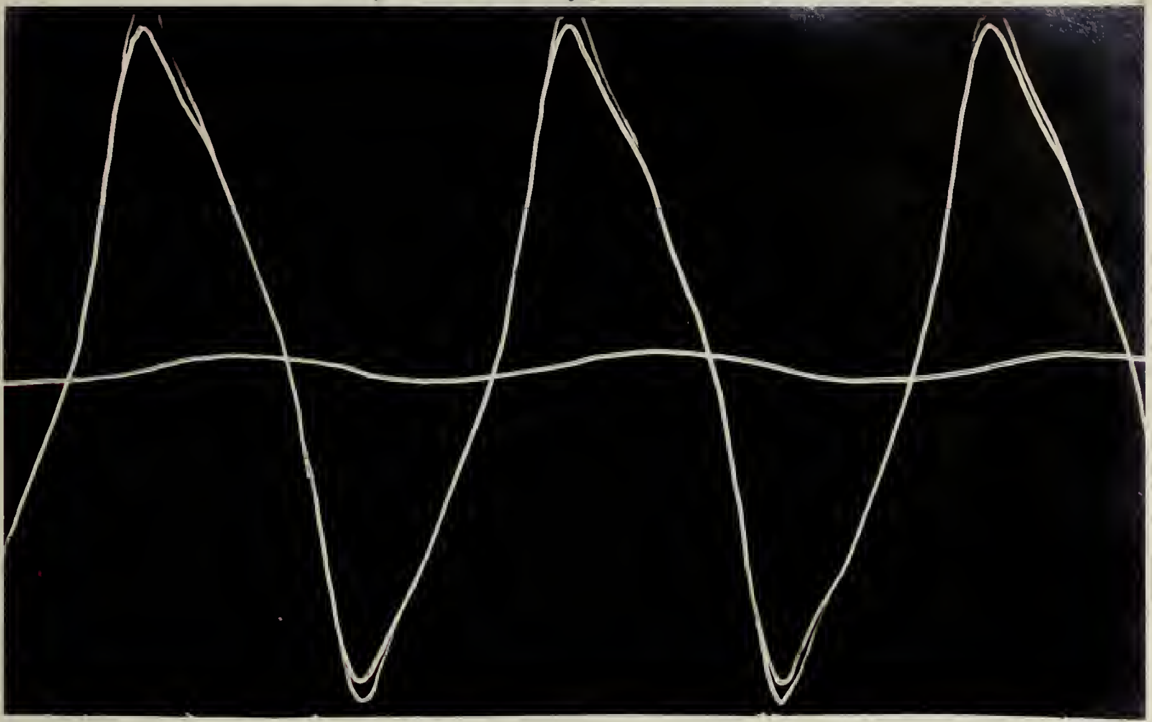
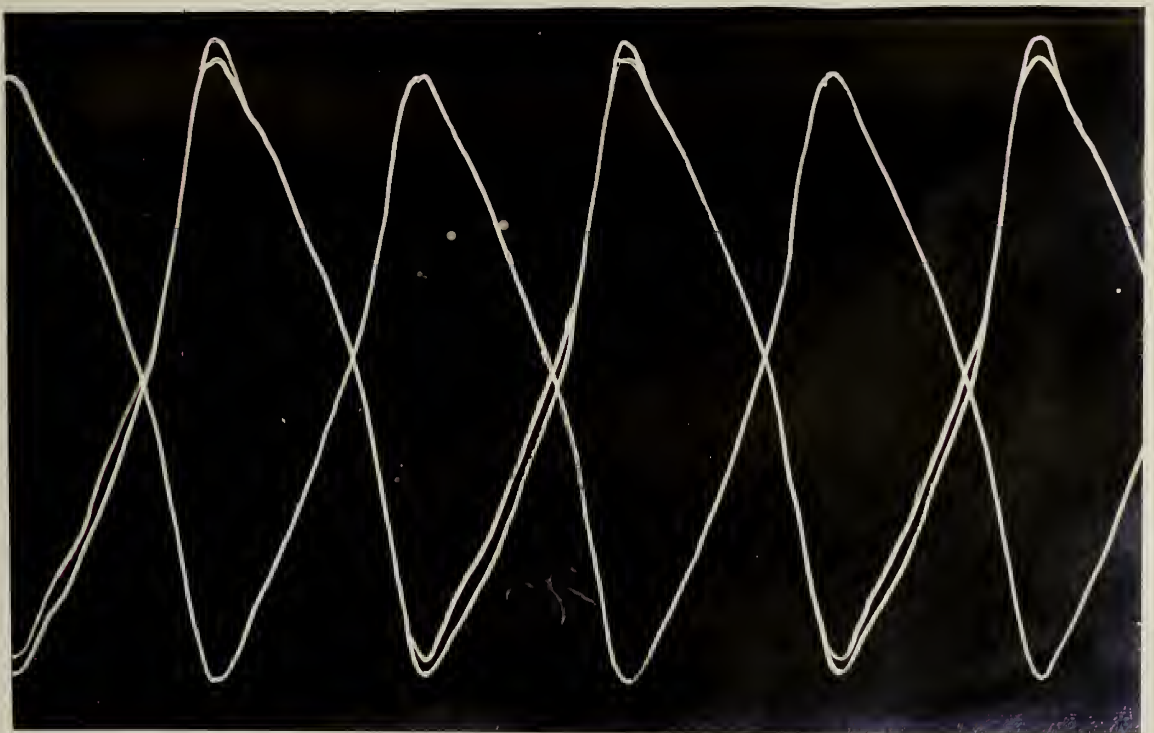


FIGURE 65, Oscillogram for Coil Current with one Coil Reversed in a 3 ∅ Shell Type Transformer.



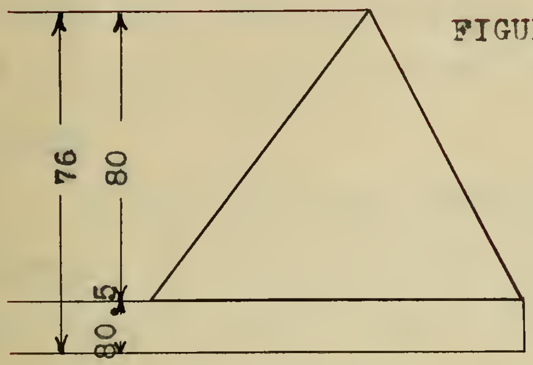
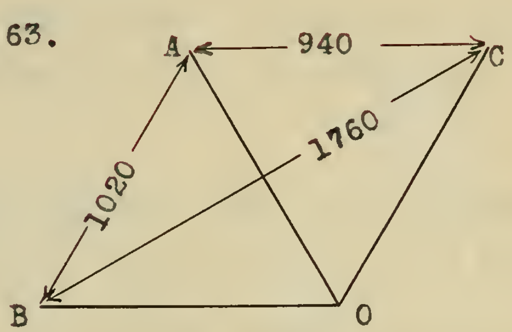


FIGURE 63.



the secondary connected in Y. It was impossible to get to the neutral on the high side so no coil voltages could be obtained. The voltage across coil A is the same as that across OB or OC but OA is reversed in direction due to the reversing its primary. The analysis of this condition is given very well by the oscillogram given in figure 64 and 65. It will be noticed that figure 64 shows two line currents in phase with one small value 180 degrees out of phase. Figure 65 shows the coil currents likewise, two of which are in phase and the reversed coil 180 degrees out of phase with them..

Frequent occasion arises to step up and step down the voltage by means of shell and core type transformer. In any case when these two are used one if one of the transmission lines are opened the result is the same as if the line from the generator were opened.

If a line from the generator is opened the voltage triangles for both the step-up and step-down transformers collapsed. This would be expected since previously the step-up voltage triangle would collapse and therefore the step-down transformer would have a voltage impressed on it that would be collapsed, thus making its vector diagram a collapsed.

When one coil is reversed in a step-up step-down system very little difference can be noted in the primary voltages of the

step-up transformer. The currents are very large, however, and limit the voltage that can be impressed. The current in the wire leading to the reversed coil is the only normal voltage, the other two being very large.

In the step-down transformer of the group the voltages are not balanced and here the error would be discovered, even if the current flowing was not noted. When a line was opened from the generator with this reversed condition, the vector diagrams for both transformers collaped.

By means of an oscillograph many interesting results were obtained that would not have been obtained otherwise. A study of these two types of three phase transformers gave the following results:

CORE TYPE: Maximum value of the triple = 4 volts.

Effective value of the tripe = 2.8 volts.

Coil voltage is a flat top wave.

The closed delta circulating current = .199 amperes.

SHELL TYPE:

Line voltage shows evidence of higher harmonics.

The open delta voltage shows decided higher harmonics.

Coil voltage also shows evidence of higher harmonics.

The closed delta circulating current = .437 amperes.

The open delta voltage = 21.2 volts.

Reversing a coil in this type of transformer throws two currents in phase and the other 180 degrees out of phase with the former.